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IMPACTS OF EXPLORATORY DRILLING FOR OIL AND GAS ON THE BENTHIC ENVIRONMENT OF GEORGES BANK

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INTRODUCTION

The Georges Bank is a large plateau lying within the territorial waters of both the U.S. and Canada, 80 to 325 km east of the Massachusetts coast. It is one of the most productive commercial fishery areas in the world. Many species of finfish and shellfish, including cod, haddock, flounder, ocean scallops and lobster, with a market value in excess of 165 million dollars, are harvested from Georges Bank each year (McLeod and Prescott, 1982).

In addition, the geologic structures underlying the Bank are of the type that may -contain substantial reservoirs of petroleum and/or gas. As a result, the U.S. and Canadian oil industries have for several years been interested in exploring for oil and gas on Georges Bank. Exploratory drilling in Lease Area 42 in the south-central portion of the U.S. sector of the Bank began on July 22, 1981, and the last of eight exploratory wells was completed there on September 27, 1982. All eight wells were reported to be dry. It is possible that additional exploratory wells will be drilled in the U.S. and/or Canadian sectors of Georges Bank in the future.

The major environmental concern arising from oil and gas exploration on Georges Bank is that intentional discharges of materials (mainly drilling muds and drill cuttings) from oil rigs during normal exploratory activities might damage the Georges Bank environment, particularly the animals living on or in the bottom sediments upon which commercial species depend for food. Because drilling muds and cuttings are composed primarily of insoluble solids that settle rapidly to the bottom, is is widely accepted that impacts of drilling discharges, if any occur, will be most severe in the benthos where drilling mud and cuttings accumulate (National Research Council, 1983). If commercial quantities of oil or gas are found, the major concern during the development and production phases of the Georges Bank field would be that accidental spills of crude oil and operational discharges of petroleum hydrocarbon-laden produced water would harm the biota, particularly the floating and pelagic eggs and larvae of commercial fisheries species.

The Georges Bank Monitoring Program was designed by a federal multi-agency panel to address concerns related to the initial exploratory phase of Georges Bank development. The program was funded by the U.S. Department of the Interior, Minerals Management Service (MMS). The major objectives of the monitoring program were to determine where and in what quantities materials discharged to the ocean during normal exploratory drilling operations accumulate, and if these discharges have effects on the benthic infaunal communities of Georges Bank. Results of the three major portions of this program have been described in detail in three separate reports to the Minerals Management Service. These are: benthic ecology (Maciolek-Blake et al., 1985); metals in sediments (Bothner et al., 1985); and hydrocarbons in sediments and biota and metals in biota (Payne et al., 1985).

Exploratory Drilling Discharges

During well drilling, a wide variety of liquid, solid, and gaseous wastes are produced on the drilling rig, some of which are discharged to the ocean (Neff et al., 1987). Such discharges are regulated by the Environmental Protection Agency through issuance of National Pollutant Elimination System (NPDES) permits. The major permitted discharges of environmental concern associated with exploratory drilling are drill cuttings and drilling fluids (National Research Council, 1983). Drill cuttings are particles of crushed sedimentary rock produced by the action of the drill bit as it penetrates the earth. Drilling fluids are specially-formulated mixtures of natural clays and/or polymers, weighting agents and other materials suspended in water or a petroleum material. Discharges to the ocean of water-based, but not oil-based, drilling fluids may be allowed by NPDES permit. Only water-base drilling fluids were used to drill the eight exploratory wells in the U.S. sector of Georges Bank.

The five major ingredients in water-based drilling fluids (barite, clay, lignosulfonate, lignite, and sodium hydroxide) account for over 90 percent of the total mass of additives used in water-based drilling fluids (National Research Council, 1983). The other major ingredient is fresh water or sea water. There are many other ingredients available for drilling mud formulation, but most of these are used only in small quantities to solve special problems encountered down hole while drilling.

The total amounts of drilling fluid solids used to drill the wells in Blocks 410 and 312 the two wells monitored in this investigation) were 1,193.6 and 1 524.0 metric tons, respectively (E.P. Dannenberger, Minerals Management Service, personal communication) . The drilling fluids contained 510 and 1,083 metric tons, respectively, of barite (barium sulfate) weighting agent. In addition, approximately 16,200 liters of diesel fuel

were used in the drilling fluids in Block 312 to aid lubrication and to free stuck pipe. As much as 50 percent of the drilling fluid used for each well may have been either left in the hole or lost to permeable formations.

It is estimated that approximately 600 metric tons of drilling fluid solids containing 500 metric tons of barite were discharged from the rig in Block 312 (Neff, 1987a). Payne et al. (1982) estimated that approximately 525 liters of diesel fuel were discharged with the drilling fluids from this rig. Several samples of drilling fluid collected at different times during drilling in block 312 contained 23 - 1,130 mg/liter (ppm) total petroleum hydrocarbons (Payne et al., 1983). Approximately 1,200 metric tons of drill cuttings were discharged to the ocean from each rig during drilling of the two exploratory wells.

Neff (1987a) estimated that a total of approximately 9,200 metric tons of drill cuttings and approximately 5,000 metric tons of drilling fluid solids containing 3,000 metric tons of barite and 1,500 metric tons of bentonite clay were discharged to Georges Bank during the drilling of eight exploratory wells during 1981 and 1982. Bothner et al. (1983) estimated a slightly greater discharge of barite, 4,400 metric tons.

MATERIALS AND METHODS

Field Sampling

The Georges Bank Monitoring Program was designed to determine both near-field and regional impacts of oil exploration activities . Twenty regional stations were established to assess potential impacts of drilling activities over a broad expanse of the Bank (Figure 1). Three transects of three stations each were established in an approximately north-south direction

perpendicular to the local depth profiles. The transects were located east of, west of, and directly through the Lease Sale 42 area, with the three stations on each transect located at approximately 60, 80, and 100 m water depth. Because net water movement over the southern flank of the Bank at all depths is toward the southwest (Butman et al., 1982; Chapman et al., 1986), the eastern Transect I was upcurrent of the lease area and was considered a reference transect. The western Transect III was downcurrent of the drilling activity where drilling discharges might accumulate on the bottom. Additional regional stations were located at sites of possible deposition of solids from drilling discharges. These included stations at the heads of Lydonia and Oceanographer Canyons (Stations 7, 7A, and 9), at the shelf/slope break (Station 8), in the Gulf of Maine (Stations 14 and 14A), and in the Mud Patch, an area of fine-grained sediments south of Cape Cod (Stations 13 and 13A). An additional station was located in shallow water at the top of the Bank (Station 15).

Two groups of stations were located in close proximity to two exploratory drilling sites in order to assess potential near-field impacts of drilling discharges. Three stations were located near the drilling site in Block 410 in about 142 m of water. Station 16 was located within 200 m of the rig site, and Stations 17 and 18 were located approximately 2 km upcurrent and downcurrent, respectively, of the rig site. A site-specific array of 29 stations was located in a radial pattern around Regional Station 5, the site of exploratory drilling in Block 312, in 84 meters of water (Figure 2). Stations were located at distances of 0.2, 0.5, 1, 2, 4, and 6 km from the rig site. Samples from 19 of these stations (identified as the primary stations in Figure 1) were analyzed, and samples from the remaining 10 stations (identified as secondary stations) were archived.

Positioning of the ship on each cruise was based on the Loran-C navigation network. A Northstar 6000 receiver was used to read time delays and calculate latitude and longitude. Samples

were collected when the ship was within ±0.3 us of the target time delays which were established the first time each station was sampled.

All stations were sampled four times per year on a seasonal basis for three years, between July 1981 and June 1984 (Table 1). At each station, six replicate 0.04-m^2 biology samples and three replicate 0.10-m^2 chemistry samples of undisturbed bottom sediment were collected with Van Veen grab samplers. The chemistry samples were collected with a Teflon coated grab sampler that was lowered to the bottom with a polyethylene-coated cable to minimize contamination of the samples. The chemistry grab sampler was rinsed with distilled methanol and hexane before each use.

Subsamples of the biology grabs were taken for carbon-hydrogen-nitrogen (CHN) and sediment grain-size analysis. The remainder of the sample was washed through 0.3-mm screens. The material retained on the screen plus the residue were placed in separate containers and preserved in 10 percent buffered formalin for analysis of the infauna.

Upon recovery of a chemistry grab sample, the overlying water was siphoned off with a glass tube, and the upper 2 cm of material was collected with a noncontaminating utensil. Subsamples for metals analyses were placed in acid-washed polyethylene containers; subsamples for hydrocarbon analysis were placed in steel or Teflon jars. All chemistry samples were frozen immediately after collection for transport back to the laboratory.

Bottom still photographs were taken with a Benthos Model 372 bounce-type camera at each regional and primary site-specific station to document microtopography and epifaunal densities, and in an effort to detect possible accumulations on the bottom of drilling fluid solids and/or cuttings.

Dredge and trawl samples were collected at certain stations to obtain fish (four spot flounder Paralichthys oblongus) and mollusc (ocean quahog Arctics islandica) samples for chemical analysis. The catch was emptied into an epoxy-coated wooden box, care being taken not to let any of the sample touch the deck. Samples selected for hydrocarbon analysis were rinsed with filtered sea water and wrapped in solvent-rinsed aluminum foil. Samples for metals analysis were rinsed in filtered sea water and placed in heavy-duty Ziploc bags. All samples were frozen immediately for transport to the laboratory.

Measurements were taken at all regional stations of temperature, salinity, and dissolved oxygen in bottom water. Temperature measurements were obtained with expendable bathythermographs (XBTs). Bottom water samples for salinity and dissolved oxygen determinations were obtained from a Niskin bottle attached to the winch wire above the biology grab sampler. Dissolved oxygen was determined by Winkler titration or by oxygen electrode, and salinity was determined with an Autosal salinometer.

Laboratory Analyses

Biology. In the laboratory, each infaunal sample was resieved through nested 0.5-mm and 0.3-mm screens, transferred to 70 percent alcohol, and stained with Rose Bengal. All macrofauna were sorted to basic taxonomic groups under a dissecting microscope. Identifications were made to the lowest possible taxon, usually to species, using compound microscopes.

Wet weight biomass was determined to the nearest 0.1 mg for each species from samples from the first eight cruises, and for a Portion of the samples collected on the last four cruises. Ash-free dry weight was determined for species from three replicates collected on the ninth cruise and correlated with

wet-weight biomass.

All biology data from each cruise were coded and entered onto a VAX 11/780 computer. Statistical treatment of each data set included an agglomerative clustering technique to determine similarity among samples. The primary similarity measure used was NESS, the Normalized Expected Species Shared (Grassle and Smith, 1976), in which comparison of expected species shared is between random samples of 50 individuals drawn from each sample. The clustering strategy was flexible sorting with beta set at -0.25. The Bray-Curtis coefficient was also used as a similarity measure with group average sorting (Boesch, 1977). The Shannon-Wiener diversity index (H') and the associated evenness value (E) were calculated, and Hurlbert's (Hurlbert, 1971) modification of the rarefaction method (Sanders, 1968) was used to predict the number of species in a random sample without replacement. Spearman rank correlation (Siegel, 1956) was used to test the association between variables such as density of individual species or community similarity indices and physical variables such as sediment grain size.

Bottom still photographs, each representing approximately one square meter of bottom area, were evaluated for bottom microtopography and texture. The presence and number of visible epifauna and demersal fish also were recorded. Faunal identifications were made by examining voucher specimens collected from dredge and trawl samples and by consulting taxonomic specialists and the available literature. Faunal densities per square meter were calculated for each taxon in each picture and averaged for the station.

Chemistry. Sediment samples for metals analysis were thawed, homogenized, and subsampled under a laminar flow hood. Replicate samples from some stations were blended, equal weights being used from each replicate. In other cases, each replicate was analyzed separately. Subsamples of the homogenized samples were taken for

metals analysis and for sediment grain size analysis. Samples for grain size analysis were dried to a constant weight at 70°C in an oven having Teflon-coated inner surfaces and a filtered nitrogen atmosphere.

Two types of sediment samples were prepared for metals analysis: bulk sediments and sediment fine fractions. To prepare the bulk sediment samples, shell fragments and particles larger than 2 mm were removed from the dried samples and the samples were ground in an agate grinder. Drill cuttings, identified by their angular edges and unusual color, were not removed. A sediment fine fraction was also prepared from samples from some stations in order to maximize the analytical resolution in identifying metals derived from drilling fluids. Sand and coarser material was removed from these samples by wet sieving them through a 60-um mesh nylon sieve. Filtered distilled water was used to wash the fine fraction through the sieve. The resultant slurry was dried in a Teflon-coated oven, and then ground and analyzed by the same techniques used for bulk sediments.

The analysis of metals in the sediment samples was performed by the U.S. Geological Survey Branch of Analytical Laboratories, Reston, Va. The following metals were analyzed: aluminum (Al), barium (Ba), cadmium (Cd), chromium (Cr), copper (cU), iron (Fe), lead (Pb), manganese (Mn), mercury (Hg), nickel (Ni), vanadium (V), and zinc (Zn). Samples were digested with hot $HClO_4/HNO_3/HF$, and the resulting residue was dissolved in 8N HCl. Al, Ba, and Fe were analyzed by inductively coupled argon plasma spectrometry (ICP). Cr, Ni, and V were analyzed with a graphite furnace atomic absorption spectrophotometer (AAS). Aliquots of the digestate were extracted with butyl acetate to extract iron, and the resulting aqueous phase was dried and dissolved in HCl. An aliquot of this digestate was analyzed for Mn and Zn by ICP. The remainder was extracted with diethyldithiocarbamic acid in chloroform. The chloroform extract was dried, treated with HNO_3, and dissolved in HC1. The extracts were analyzed by graphite

furnace AAS for Cd, Cu, and Pb. A separate subsample of the dried sediment was digested with hot $HNO_3/HClO_3$ and analyzed for Hg by induction furnace atomic absorption spectrophotometry. Results of Ba and Cr analyses on selected sediment samples were cross-checked by an X-ray fluorescence technique (Johnson, 1984) .

Analytical accuracy was determined by analyzing the rock standard, MESS-1 , and was found to be excellent. Analytical precision was determined by periodically analyzing replicate aliquots taken from a single sample. Coefficients of variation for replicate samples indicated that the standard deviation was typically less than 10 percent of the mean value, except when concentrations were near or at the detection limit of the method.

A detailed description of the methods for processing and analysis of sediment and biota samples for hydrocarbons and biota for metals is given by Payne et al. (1982). Sediment samples were thawed, dehydrated with methanol, and extracted with methylene chloride/methanol. The combined methanol and methylene chloride/methanol extracts were back extracted with saturated sodium chloride in distilled water and evaporated to about 10 ml. Lipids in the extract were saponified with KOH and the extract was dried with sodium sulfate, concentrated, and solvent-exchanged with cyclohexane.

Some sediment extracts, selected because UV-fluorescence indicated the presence of significant concentrations of aromatic hydrocarbons, were also analyzed by gas chromatography. These extracts were added to a silica gel column and eluted sequentially with hexane (aliphatic hydrocarbons), hexane:benzene (aromatic hydrocarbons) , and methanol :methylene chloride (polar compounds) . The column fractions were analyzed on a Hewlett-Packard 5840A gas chromatography equipped with a 30-m, SE-54 wall-coated open tubular, fused silica capillary column and a flame-ionization detector. Selected aromatic extracts were also analyzed by gas chromatography/mass spectrometry using a Finnigan

4021 quadruple mass spectrometer.

Tissue samples were thawed, homogenized, and extracted with methylene chloride. The extracts were dehydrated with anhydrous sodium sulfate, concentrated, saponified, dried, and solvent-exchanged with cyclohexane as was done with sediment extracts.

The cyclohexane extracts were screened for aromatic hydrocarbons by synchronous scanning ultraviolet fluorescence spectrophotometry. The spectra were obtained over the range of 230 to 600 nm with a 30-nm offset between excitation and emission wavelengths . Semiquantitative estimates of the concentration of polycyclic aromatic hydrocarbons in the extracts were obtained by comparison of fluorescence intensities at selected wavelengths with those of mixed standard solutions containing one-, two-, and three-ring aromatic hydrocarbons.

Selected clam and demersal fish samples were also analyzed for the same suite of metals as were analyzed in sediments. Tissue samples were thawed, freeze dried, and ground to a powder. The powdered samples were ashed in a low temperature asher using a $CF_4/0_2$ plasma, and digested with hot HNO_4. The digests were analyzed by flame or graphite furnace AAS for Al, Cd, Cr, Cu, Fe, Pb, Ni, and Zn. Ba and V in the digests were analyzed by instrumental neutron activation analysis. For Hg analysis, wet tissues were diced and digested sequentially with $'^{N0}4$, hot $'2^{s0}4'$ and $KMnO_4$. Samples were treated with $NH_2OH.HCl$ in NaCl to remove excess $KMnO_4$, and with a 20% solution of $SnCl_2$ in HCl to reduce all mercury to the elemental state. Samples were analyzed by cold vapor AAS. Analytical accuracy was evaluated by analyzing National Bureau of Standards (NBS) oyster tissue (Standard Reference Material (SRM) #1566) and N.B.S. bovine liver (SRM #1577). Analytical precision was evaluated by analysis of replicates and sample splits.

Sediment grain size distribution was determined using a Rapid Sediment Analyzer for the sand fractions (Schlee, 1966). The silt and clay fractions were analyzed by standard pipette analysis or with a coulter counter.

RESULTS

Hydrography

The near-bottom waters of Georges Bank are a relatively stable environment with respect to the hydrographic parameters, temperature, salinity, and dissolved oxygen concentration. In general, the deeper stations were less variable seasonally than the shallower stations. Below about 100-110 m water depths, seasonal patterns of change in hydrographic parameters were small and inconsistent from year to year.

The distribution of bottom water temperature in the study area showed characteristic seasonal patterns. Stations below 100 m on the southern slope of the Bank had higher bottom water temperatures than did shallower stations in the fall, winter, and spring. The opposite trend occurred in the summer. The highest water temperatures were recorded at Station 15, the shallowest station, in the summer (15.3°C) and Stations 14 and 17 in the spring (16.8°C). The lowest temperatures were recorded at Stations 4 and 15 in the winter (3.8°C). Bottom water temperatures varied seasonally by more than 10°C at station 15, but remained near 10°C throughout the three years of the monitoring program at stations deeper than about 100 m.

Salinity of the bottom water on Georges Bank varied seasonally and at different stations from 31.0 to 35.5 parts per thousand (ppt). The lowest salinities were recorded at stations in less than 100 m water depth in winter. Highest salinities were recorded at stations deeper than 100 m in the summer. At any one station, salinity of bottom water varied seasonally by no more

than 2-3 ppt.

The seasonal variation in the concentration of dissolved oxygen in bottom water had a similar pattern at all stations. Dissolved oxygen concentration was highest in the winter and declined gradually with season from spring to summer to fall. In any season, highest dissolved oxygen concentrations were recorded at the shallowest stations and lowest values were recorded at the deepest stations. Percent saturation of bottom water with oxygen ranged from 43 percent at Station 8 in November 1981 to 113 percent at the same station in February 1982. Most values were in the 60-80 percent saturation range, which is sufficiently high to be non-stressful to nearly all benthic and demersal animals. Although drilling fluids have a high apparent biological and chemical oxygen demand (Breteler et al., 1985), there was no evidence that oxygen concentrations in the bottom waters near the drilling sites in Blocks 312 and 410 (Stations 5-1 and 16) were depressed during the period when drilling was taking place and drilling fluids were being discharged to the ocean.

Sediment Characteristics

Grain Size. Surficial sediments in the Study area are predominantly (more than 95 percent) quartz sand with minor amounts of gravel, shell hash, silt, and clay. The coarse texture of the sediments at most stations on Georges Bank is due to the strong winnowing processes associated with strong tidal and storm-generated currents on Georges Bank (Butman et al., 1982; Parmenter et al., 1984). Areas of high (25 to 90 percent) silt + clay content are located at the head of Lydonia Canyon (Station 7A), the area south of Cape Cod known as the Mud Patch (Stations 13 and 13A) and the southern Gulf of Maine (Station 14A). These are thought to be depositional areas (Bothner et al., 1981; Twichell, 1982; Twichell et al., 1981). There was a slight increase in the percent of material finer than 0.125 mm in sediments with increasing water depth. There also was a clear

gradient of increasing silt + clay concentration in sediments from the northeast to the southwest along the 70-80 m depth contours. (Stations 2, 5-1, 11, 13, 13A).

The concentration of gravel in the sediments ranged from O to almost 20 percent. Drill cuttings, identified by their sharp, angular configuration, were observed in the gravel fraction at the drill sites in Block 312 and 410 (Stations 5-1 and 16) after drilling. A small amount of cuttings was also observed in sediments at Station 17, 2 km to the east of the drill site in Block 410 during both year 2 and 3. One year after termination of drilling, cuttings were found in sediments from all stations within 0.5 km of the drilling site in Block 312 (Stations 5-1 through 5-5). Cuttings ranged in size from 2 to 8 mm and most were gray in color. X-ray diffraction analysis revealed that they were composed primarily of calcite, a common mineral in the subsurface Jurassic and Cretaceus sediments of the area (Arthur, 1982). Cuttings never represented more than 1.5 percent of the mass of surficial sediments at a station and were neve r observed to form a recognizable pile, as has been observed at other outer continental shelf drilling sites (EG&G Environmental Consultants, 1982).

During the three years of the monitoring program, there was a 10 to 20 percent by weight increase in the concentration of sine-grained sediments at the canyon head stations (Stations 7, 7A and 9), the Mud Patch stations (Stations 13 and 13A), and at Station 16 near the rig site in Block 410. There were 2 to 5 percent by weight increases in the concentration of fine sediments at all site-specific stations and at Regional Station 12 between the first and last sampling. These increases in fine-grain sediments near rig sites and in depositional areas could be due to accumulation of drilling mud solids or to long-term storm-related trends in sediment resuspension and transport. However, successive samplings along local small-scale gradients or in areas of patchy sediments also could account to

some extent for these trends. At several stations, there also were clear seasonal trends in sediment grain-size distribution, with percent coarse fractions increasing in winter months and decreasing in summer months. These seasonal patterns undoubtedly reflect storm-induced resuspension and transport of fine-grain sediments during winter months.

Microtopography. The surface texture of sediments, as revealed by bottom still photographs taken at most stations on all 12 cruises, varied with depth and season. At Stations 1, 4, and 10 along the 60-m isobath, the sediment was a clean, well-sorted sand containing small amounts of shell hash. The sediment surface was asymmetrically rippled with some sculpturing.

Stations 3, 6, and 12 along the 100-m isobath had silty sand sediments containing many large shell fragments of the ocean quahog Arctics islandica. A uniform layer of silt and fine detritus covered most of the shell fragments. The bottom was smooth and flat with some disturbed areas and animal burrows. Sediments at Station 7A resembled those at Stations 3, 6, and 12, except that they contained lesser amounts of shell fragments. Sediments at Stations 8 and 9 in 145 m of water were silty sand with small amounts of biological material and shell hash present. The surface was sculptured or smooth and various biogenic features were evident.

Sediments at Stations 16, 17, and 18, located in close proximity to one another in 140 m of water in Block 410, contained silty sand with small to medium sized shell fragments. There was a uniform cover of coarse detritus and/or biological material present. Ripples sometimes were observed on the surface of the sediment at these stations during the winter.

Stations 2 and 11 in 80 m of water resembled the site-specific stations. All the site-specific stations, with the

exception of Station 5-29, had sandy sediments covered by a fairly uniform layer of coarse detritus and/or biological material. Scattered shell fragments were also present. The topography was flat with many biogenic features.

Consistent seasonal changes were evident at nearly all site-specific stations. Smooth, unsculptured surfaces with fairly uniform detritus coverage were typical in the spring and summer. In the fall and winter, the sediment surface was rippled and sculptured and clumped, patchy detritus was visible.

Metals. Before drilling began, the concentrations of metals in sediments from all stations were low compared to their average concentrations in crustal rocks and were characteristic of uncontaminated coarse-grained marine sediments. The highest concentrations of all metals analyzed were in sediments from Station 13, the Mud Patch station. Lead was the only metal in predrilling sediment samples from Station 13 that was present at a concentration higher than its mean concentration in crustal rocks. The differences in metals concentrations in sediments from different stations was directly correlated with the concentrations of fine-grained material in the sediments.

Throughout the three years of the monitoring program, there was no increase in the concentration of any metal except barium in bulk sediments from any station. Concentrations of barium increased in bulk sediments from stations adjacent to the platforms in Blocks 312 and 410 after the start of drilling.

Bulk Sediments, Block 410. Drilling began at Block 410 immediately after the first sampling cruise in July 1981 and continued (with some interruptions) until March 31, 1982, shortly after the third cruise (10-21 February 1982). At Station 16, located within 200 m of the drilling site, the average concentrations of barium in bulk sediments increased steadily from a predrilling concentration of 32 mg/kg (ppm) to a maximum

concentration of 172 ppm at the time of Cruise 6 (November 1982) (Figure 3). This represents a 5.9-fold increase in the concentration of barium. There was not a statistically significant difference between barium concentrations in sediments collected on Cruises 4 (first postdrilling cruise), 5, and 6, but the mean values for samples from these cruises were significantly higher than the mean value for the samples from Cruise 1. After Cruise 6, mean concentrations of barium in sediments at Station 16 decreased to about 80 ppm. The wide variation in values among replicates and sampling times indicates that barium is not distributed homogeneously over the sampling area. This heterogeneity is probably caused by the intermittent discharge of drilling fluids into a current field that continually changes direction of flow throughout the tidal cycle.

As expected, because mean current flow in this. region of the Bank is toward the southwest, concentrations of barium were higher in bulk sediments from Station 18 located 2 km west of the drill site than in sediments from Station 17 located 2 km east of the drill site (Figure 3). The maximum increase in sediment barium concentration at Station 18 was about 2-fold at the time of Cruise 2 approximately four months after the start of drilling in Block 410. The mean concentrations of barium decreased to predrilling levels at the time of Cruises 8 and 9, and then increased again. At the time of Cruise 12, the mean sediment barium concentration was 36 percent higher than the mean predrilling level. This difference was statistically significant at the 99-percent level of confidence.

At Station 17, the maximum increase in mean sediment barium concentration was 1.3-fold at the time of Cruise 2. Barium concentrations decreased to background by Cruise 8 and 9, followed by an apparent increase in sediment barium concentration at the time of Cruise 12. However, the mean concentration of barium in sediment at the time of Cruise 12 was not significantly

different from the value for sediment barium at the time of Cruise 1.

Concentrations of chromium in bulk sediments from Stations 16, 17, and 18 did not increase after the start of drilling. There also was no change in the concentration of other metals in bulk sediments from these stations during the three years of the monitoring program.

Sediment Fine Fraction, Block 410. The concentrations of barium increased dramatically in the fine fraction of sediments (the fraction finer than 60 urn) from the three stations near the drilling site in Block 410 (Figure 4) after initiation of drilling. At Station 16 adjacent to the rig site, barium concentrations in the sediment fine fraction increased from a predrilling mean of 242 ppm to the range of 8,000 to 10,000 ppm between the third and the seventh cruises. By the time of the twelfth cruise, approximately 27 months after completion of drilling in Block 410, the concentration of barium in the fine fraction of sediments at Station 16 was still more than ten times higher than in the predrilling samples from this station. As expected, the concentration increases of barium in the fine fraction of sediments from Stations 17 and 18 were less than those at Station 16, and the increase in barium concentration at the down-current station (Station 18) was greater than the increase at the up-current station. Barium was quite persistent in the fine fraction of sediments from Station 18.

The concentration of chromium in the fine fraction of sediments from Station 16 increased about two-fold between the predrilling cruise and the third cruise (Figure 4). Chromium concentrations then returned to the predrilling range by the time of the fourth cruise. There was no increase in the concentration of chromium in the fine fraction of sediments at either Station 17 or 18. The concentrations of aluminum, copper, and mercury in the fine fraction of sediments from Station 16 increased slightly

above the predrilling levels by the time of the third cruise and then returned to predrilling levels by the time of the fourth cruise. The concentrations of these metals and the other metals analyzed did not increase in the fine fraction of sediments from Stations 17 and 18 at any time during the monitoring program.

Bulk Sediment, Block 312. In Block 312, the site of the site-specific survey, drilling began on December 8, 1981, shortly after the completion of Cruise 2 (2-21 November 1981), and was completed in June 1982, approximately a month before Cruise 5 (21-28 July 1982). There were increases in the concentrations of barium at several stations within 1 km of the drill site (Figure 5). The greatest increase in the concentration of barium in bulk sediments between the predrilling cruises and the postdrilling cruises was at Station 5-1, the station located within 200 m of the drilling site. The increase here was 4.7-fold from a mean of 28 ppm at the time of Cruise 1 to a mean of 131.7 ppm at the time of Cruise 5. At this station, there were large standard deviations among the three replicates at each sampling time and between mean values for different cruises, reflecting a very heterogeneous distribution of drilling fluid-derived barium in sediments at the site. There were slightly larger increases in mean barium concentrations in bulk sediments at stations 0.5 km or more to the west of the drilling site than in sediments to the east of the drilling site, reflecting the net westward mean current drift in the region. At all stations except Station 5-10, located 1 km west of the drilling site, the maximum increment in barium concentration in bulk sediment occurred at the time of Cruise 5 which was conducted immediately after completion of drilling in Block 312. At Station 5-10, the greatest increment occurred at the time of Cruise 4. At Station 5-29, located 6 km west of the drilling site, there was a 1.4-fold increase in the concentration of barium in bulk sediment between Cruise 1 and Cruise 5. This was the farthest station from a drilling site at which an increment in barium concentration in bulk sediment, attributable to drilling fluid discharges, was observed.

There was no change in the concentration of chromium (Figure 5) or any of the other metals analyzed, other than barium, in bulk sediments from any of the stations in the site-specific array around the rig site in Block 312.

Sediment Fine Fraction, Block 312. The concentrations of barium in the fine fraction of sediments from the site specific array in Block 312 increased substantially after drilling began there (Figure 6). At most stations, concentrations of barium in the fine fraction of the sediments dropped after drilling was completed. However, there were different trends in the temporal pattern of change in barium concentrations in the fine fraction of sediments at different stations along an east west transect through the drilling site. At Station 5-28, the easternmost station, the increase in barium concentration was less than at most other stations and returned to the range of the predrilling values by the time of Cruise 7. At Station 5-2, 0.5 km east of the drilling site, barium concentration in the fine fraction of sediment reached a maximum at the time of Cruise 4, just before termination of drilling, and remained high at the time of Cruise 5, just after the completion of drilling. Barium concentrations for Cruises 6 through 12 then dropped to about five times the predrilling values. The barium concentration in the fine fraction of sediments from Station 5-18, 2 km west of the drilling site, reached a maximum at the time of Cruise 5, and then decreased to two to four times the predrilling level for Cruises 6 through 12. At Station 5-29, the most westerly site-specific station located 6 km west of the rig site, the concentration of barium in the fine fraction of sediments showed a continuing increasing trend from Cruise 1 (redrilling) through Cruise 12 (two years after completion of drilling in Block 312). The continued increase in barium concentration in the fine fraction of sediments from this station may have been caused by the transport to and deposition in the area of sediments contaminated with drilling fluids solids from depositional sites near the drilling site.

In an effort to learn how far barium from drilling fluids could be traced, the fine fraction of sediments from Stations 10 and 12, approximately 65 km west of the drilling site in Block 312, and Stations 2 and 3, approximately 35 km to the east of the easternmost drilling site were analyzed for barium. At Station 10, there was a 6.4-fold increase in the concentration of barium in the fine fraction of sediment from 94 ppm before drilling began to 604 ppm at the time of Cruise 10, 17 months after the completion of drilling in Block 312. At Station 12, with finer grained sediments than at Station 10, the concentration of barium increased 3.7-fold from 220 ppm before drilling began to 820 ppm at the time of Cruise 8, 11 months after the completion of drilling in Block 312. At Stations 2 and 3, located east (upcurrent) of the drilling sites, there was a statistically significant approximately 2-fold increase in the concentration of barium in the fine fraction of sediment between either Cruise 5 or 1, respectively, and Cruise 7, eight months after completion of drilling in Block 312. There was also an highly significant increase in the ratio of barium to aluminum concentration in the fine fraction of sediments from the three stations for which aluminum data were available (Stations 2, 3, and 12) at the time of Cruise 7 or 8. Because aluminum concentration is highly correlated with the percent clay minerals in marine sediments, the elevation in the Ba/Al ratio indicates that the increase in the concentration of barium was not due to a concomitant increase in sediment clay concentration but probably was due to an influx of barium from another mineral source (eg., barite).

Hydrocarbons. A total of 200 sediment samples from Stations 2, 5-1, 5-18, 5-28, 7A, and 13 were screened by UV/fluorescence for aromatic hydrocarbons. If the UV/F screen indicated the presence of concentrations of aromatic hydrocarbons significantly above the apparent background concentration of several hundred nanograms per gram (parts per billion; ppb), the samples were analyzed further by gas chromatography-flame

ionization detection (GC-FID) or gas chromatography-mass spectrometry (GC-MS).

Mean concentrations of total aromatic hydrocarbons, as determined by UV/F, in sediments from Station 5-1 within 200 m of the drilling site in Block 312 were approximately 100 ppb prior to initiation of drilling (Cruises 1 and 2) (Figure 7). During drilling (Cruises 3 and 4), mean concentrations of total aromatic hydrocarbons in sediments increased to 430 ppb and remained fairly constant at about 400 ppb throughout the remainder of the monitoring program. A one-way analysis of variance on log-transformed data indicated that the variance in concentrations among cruises was significantly greater than expected by normal distribution. Furthermore, the results of Duncan's multiple range test indicated significant differences at the 95 percent confidence level in total aromatic hydrocarbon concentrations in sediments collected during Cruises 1 through 3, compared to sediments collected during cruises 4 through 12.

Sediment samples collected from Station 5-1 during Cruises 1, 3, 4, and 8 were subjected to further analysis by GC-FID to identify possible sources of the hydrocarbons contained in the samples. Chromatographic profiles of the aliphatic hydrocarbon fraction of the sediment sample collected on Cruise 1 were characterized by a relatively flat baseline, the general absence of an unresolved complex mixture (UCM), and the absence of a homologous series of n-alkanes typical of petroleum hydrocarbons. There was a strong odd carbon predominance in the higher molecular weight aliphatics, suggestive of a biogenic source of the hydrocarbons. There were trace levels of branched alcohols in the aromatic fraction of the sample. The absence of polycyclic aromatic hydrocarbons (PAH) and the corresponding low concentration of total aromatic hydrocarbons (approximately 100 ppb) associated with this sample suggest that no previous accumulation of petroleum hydrocarbons had occurred at Station 5-1.

Gas chromatograms of extracts of sediments collected at Station 5-1 on Cruises 3 and 4 during drilling were quite different from those from samples from Cruise 1. The aliphatic fraction of the sample from Cruise 4 contained suites of even and odd n-alkanes from nC_8 to nC_{22} and primarily odd n-alkanes from "23 '0 "32 " This fraction also contained a large UCM in the Kovats index range of 2100 to 3500. The aromatic fraction chromatogram from this sample was much more complex than the chromatograms from any other samples. It contained several PAH which were identified subsequently by GC/MS (Table 2). The most abundant PAH in the sample were naphthalene, fluorene, phenanthrene, and pyrene and their alkyl homologies. Many of the PAH present in the sediment sample were also present in samples of diesel fuel-contaminated drilling fluids from the platform in Block 312 (Payne et al., 1982). The repeating< series of n-alkanes, the presence of several PAH, and the presence of UCM all provide strong evidence of the presence of petroleum hydrocarbons in sediments from Station 5-1 at the time of Cruise 4. these hydrocarbons probably were derived from the discharge of diesel fuel-contaminated drilling fluids from the drilling rig in Block 312.

With one exception, the chromatograms of extracts of sediments collected at Station 5-1 after termination of drilling in Block 312 revealed little evidence of petroleum contamination. The chromatograms of the aliphatic fractions were devoid of a UCM or a homologous series of low to intermediate molecular weight n-alkanes, and n-alkanes 'n 'he "21 '0 "31 range exhibited a strong odd carbon predominance. Chromatograms of the aromatic fraction were characterized by the general absence of resolved lower molecular weight compounds, a relatively small UCM, the presence of biogenic alcohols, and the absence of PAH. The one exception was a single replicate sample taken on Cruise 9. The aliphatic fraction of this sample was characterized by a large UCM from nC_{17} '0 "25 and a bimodal suite of medium molecular

weight n-alkanes as a homologous series from nC_{18} to nC_{21} and an odd carbon predominance from nC_{23} to nC_{31}. The two patterns of n-alkane peaks suggest that more than one source contributed to the observed hydrocarbon profiles. The aromatic fraction of this sample was characterized by a general absence of low molecular weight compounds, a small UCM, and the presence of several high molecular weight compounds. The relative complexity of the sample is also reflected by the unusually high concentration of total aromatics (0.99 ppb) as measured by UV/F. This anomalous sample could be the result of sample contamination or it could indicate a heterogeneous distribution in sediments near the drilling site after completion of drilling of materials associated with drilling discharges.

Mean concentrations of aromatic hydrocarbons, based on UV/F, in sediments at Station [illegible], located 2 km west of the drilling site in Block 312, showed a gradually rising trend during the three years of the program. However, there was substantial variability among replicates for Cruises 9 through 12. The coefficient of variation associated with the mean values for samples from each of these cruises ranged from 36 to 71 percent. Mean concentrations of total aromatic hydrocarbons in predrilling samples (Cruises 1 and 2) were less than 100 ppb; mean concentrations during drilling and the second year of monitoring were in the range of about 50 to 200 ppb; and mean concentrations of total aromatic hydrocarbons during year three of the program were in the range of 170 to 460 ppb. GC-FID analysis of replicate samples from this station collected on Cruise 9 revealed evidence that at least one of the replicates contained petrogenic hydrocarbons. The aliphatic fraction of this sample contained a bimodal suite of n-alkanes, comprising a series of medium molecular weight compounds from nC_{15} through nC_{23}, with an unresolved complex mixture and a series of high molecular weight alkanes with a clear odd carbon predominance. GC/MS analysis of the aromatic fraction of this sample revealed the presence of several PAH, including methyl phenanthrene,

fluoranthene, pyrene, and chrysene at sub-ppb levels. These results indicate a possible down-current transport of drilling discharges from the vicinity of the drilling site.

Sediments from Station 5-28, located 6 km east (upcurrent) of the drilling site in Block 312, contained low concentrations of total aromatic hydrocarbons, as indicated by UV/F . Mean concentrations of total aromatic hydrocarbons in sediments were at or below 100 ppb at all sampling times except Cruise 3 during drilling. The mean concentration of total aromatic hydrocarbons in the Cruise 3 sediment samples was 220 ppb . One of these samples was analyzed by GC-FID and GC/MS. The sample contained 1 0w concentrations (1 to 8 ppb) of several medium and high molecular weight PAH, indicating possible contamination with petrogenic hydrocarbons.

The mean concentrations of total aromatic hydrocarbons, as measured by UV/F, in sediments from Station 2 were below 100 ppb at all sampling times and there were no temporal trends of change in hydrocarbon concentrations. Several sediment samples from this station collected on the first four cruises were analyzed by GC-FID. These analyses revealed no evidence of petrogenic hydrocarbons.

Stations 7A and 13 are both depositional sites with relatively fine-grained sediments. Therefore, it is not surprising that concentrations of total aromatic hydrocarbons in sediments from these stations, as measured by UV/F, were higher than in sediments from the site-specific stations. Mean aromatic hydrocarbon concentrations measured in sediment samples collected at Station 7A on Cruises 5 through 12 ranged from 1.2 to 2.2 ppm. GC-FID analyses of several composite samples obtained at this station on different cruises revealed the presence of 1 0w concentrations of several low molecular weight PAH, including naphthalene, 2-methylnaphthalene, biphenyl, fluorene, and dibenzothiophene . The presence of these PAH indicates the

presence of petrogenic hydrocarbons in the sediments from this site. However, both the absence of the highly branched alkyl-substituted PAH and the lack of the numerous other higher molecular weight PAH that are characteristic of the drilling fluids from the rig in Block 312, indicate that the petroleum hydrocarbons in sediments at Station 7A probably were not derived from discharges of drilling fluids from the platform in Block 312.

The mean concentrations of total aromatic hydrocarbons in sediments collected at Station 13 on Cruises 1 through 12 ranged from 90 to 250 ppb and did not show a consistent temporal trend. The highest concentrations of total aromatic hydrocarbons were observed in samples from Cruise 4 (during drilling) and Cruise 2 (immediately before drilling). The lowest mean concentrations were observed in samples from Cruises 6 and 7. Several sediment samples from this station were analyzed by GC-FID. Chromatograms of the aliphatic fractions were characterized by a series of n-alkanes with an odd carbon predominance in the nC_{23} to nC_{33} range and a UCM. Several alkyl PAH were identified in the aromatic fractions at concentrations of 1 to 20 ppb. The hydrocarbon profiles did not resemble those of drilling fluids from Block 312. The hydrocarbons in sediments from Station 13 probably were derived from sources other than drilling discharges.

Contaminants in Demersal/Benthic Animals

Metals. Ocean quahogs Arctics islandica from several stations in the site-specific array around the platform in Block 312 and from Station 1 and 10 were collected on one or more cruises and analyzed for the same suite of eleven metals that were analyzed in sediments. Concentrations of all metals in the clam tissues were quite variable over time, but uniformly low at all times and stations during the monitoring program (Table 3). There were no temporal trends of increasing body burdens of any

metals at any station. Concentrations of barium, the only metal showing drilling-related increases in bulk sediments near the two drilling sites monitored, in whole soft tissues of clams from site specific stations ranged from 0.187 ppm in clams collected from Station 5-3 on Cruise 9 to 2.61 ppm in clams from Station 5-15 on Cruise 6. Four clams collected from Station 1, upcurrent of the drilling sites, contained 0.091 to 0.668 ppm barium in their soft tissues. There was no relationship between the concentration of barium in sediments from a station and the concentration of barium in the tissues of clams from that station. Mean concentrations of seven metals (Cd, Cr, Cu, Fe, Ni, Pb, and Zn) in clams collected during the monitoring program were in the same range as the concentrations of the same metals in clams collected from Georges Bank in 1978 by ERCO (ERCO, 1978).

Four spot flounder Paralichthys oblongus were collected on Cruise 4 from Stations 1, 5-1, 5-28, and 13, on Cruise 5 from Station 5-14, and on Cruise 6 from Station 13. Concentrations of all 11 metals in muscle tissue of the flounder were substantially lower than the concentrations of the same metals in flounder liver tissue or in whole soft tissues of clams (Table 4). There was no relationship between the concentration of any metal in flounder muscle and station location or sampling time. Concentrations of all metals except zinc were higher in liver of a single flounder sample from Station 5-1 (200 m from the drilling site) than in liver from a single flounder from Station 5-28 (6 km east of the drilling site) at the time of Cruise 4, shortly before completion of drilling in Block 312. Because of the lack of replication, it is not possible to draw conclusions about the significance of these results.

Hydrocarbons. Quahog clams Arctics islandica were collected for hydrocarbon analysis at Station 5-3, located 0.5 km north of the rig site in Block 312, on Cruises 5, 6, 8, 9, 11, and 12. Mean concentrations of total aromatic hydrocarbons? as analyzed by UV/F, in clams from the second year of the

program (Cruises 5 through 8) ranged from 560 to 1,150 ppb; mean concentration in clams from the third year ranged from 3,500 to 4,030 ppb. The reasons for the apparent increase in concentrations of total aromatic hydrocarbons in clam tissues from year 2 to year 3 are not known. Several of the year 3 samples were analyzed by GC-FID and GC/MS. Concentrations of total hydrocarbons, measured by GC-FID, in these samples ranged from 19,000 to 57,500 ppb. However, no high molecular weight PAH were identified by GC/MS in the samples. A few alkyl benzenes and several aldehydes and alcohols were identified in the aromatic fraction. A sample consisting of a single clam collected from Station 5-3 on Cruise 5 also was analyzed by GC-FID and GC/MS. The concentration of total aromatic hydrocarbons, as measured by GC-FID, in this sample was 2,500 ppb. However, four aromatic hydrocarbons (o-xylene, cumene, phenanthrene, and fluoranthene) were identified in the aromatic fraction at concentrations ranging from less than 2 to 110 ppb.

The temporal pattern of total aromatic hydrocarbon concentrations in clams from Station 1 was similar to that observed in clams from Station 5-3. The mean concentrations of total aromatic hydrocarbons, as measured by UV/F, in whole clam tissues collected during year 2 program ranged from 5 to 300 ppb; mean concentrations of total aromatic hydrocarbons in clam tissues collected during year 3 of the program ranged from 840 to 1,700 ppb. GC/MS analysis of a clam sample from Cruise 9 showed no evidence of high molecular weight PAH. A majority of the compounds identified in the aromatic fraction by GC/MS were biogenic sterols, alcohols, and aldehydes. Therefore, there was no evidence of an accumulation of petrogenic hydrocarbons in the clams. The observed increase in total fluorescing compounds in the clam tissues can be attributed to natural changes in the levels of biogenic fluorescent materials in the clams.

Only a limited number of four spot flounder Paralichthys oblongus were obtained for hydrocarbon analysis. Flounder samples

were obtained on Cruise 4 from Stations 5-1, 5-28, and 13, on Cruise 5 from Station 5-14, and on Cruises 6 and 8 from Station 13. Concentrations of total aromatic hydrocarbons, as measured by UV/F, in individual muscle tissue samples ranged from 20 ppb (Cruise 5, Station 5-14) to 1,640 ppb (Cruise 4, Station 5-28). The only stations from which there were flounder samples from more than one cruise was Station 13. At this station, concentrations of total aromatic hydrocarbons in flounder muscle tissue were higher in samples from Cruise 4 than from Cruises 5, 6, and 8. However, there was insufficient replication to ascertain if this trend was real. A sample of muscle tissue from a flounder collected at Station 13 on Cruise 6 was analyzed by GC/MS. Several aromatic hydrocarbons were identified in the aromatic extract of this sample at concentrations ranging from 2 to 1,200 ppb. The aromatic hydrocarbons identified in the muscle tissue include toluene, p- and o-xylene, C_6-benzene, 2-methyl naphthalene, biphenyl, and phenanthrene. The remaining components of the aromatic fraction were mainly biogenic sterols, aldehydes and "alcohols. The hydrocarbon profiles from GC analyses of flounder tissues did not resemble those from drilling fluids from the rig in Block 312, and therefore, the hydrocarbons in the flounder tissues probably were not derived from drilling discharges.

Benthic Fauna

Epifauna and Demersal Fish. A total of 31 taxa was identified in bottom still photographs taken at most stations on all 12 cruises. There were 15 species of invertebrates and 16 species of fish. The most abundant species at regional stations were asteroid echinoderms, which were present at all but one station. Other frequently occurring taxa were hake, Urophycis Spp., and cancer crabs, Cancer Spp.. The sand dollar, Echinarachnius parma, had the greatest densities where it

occurred, but it was present at relatively few stations, primarily Stations 1, 4, and 10 along the 60-m isobath.

Site-specific stations were dominated by asteroid echinoderms, with individuals belonging to the general Asterias and Leptasterias being the most common. Other taxa that occurred frequently at site-specific stations included colonial hydroids, ocean scallops Placopecten magellanicus, cancer crabs, Cancer spp., and rays, Raja spp.. The two regional stations located at the same depth as the stations in the site-specific array (Stations 2 and 11) had a different microtopography and different epifauna than the stations in the site-specific array. The epifauna at Stations 2 and 11 resembled that at Stations 1, 4, and 10 along the 60 m isobath and was dominated by Echinarachnius parma, hydroid colonies, asteroid echinoderms, and the ocean scallop Placopecten magellanicus. No E. parma were present at the site-specific stations.

Stations 16, 17, and 18 near the drilling site in Block 410, were dominated by asteroids. Stations 16 and 17 also had abundant onuphid polychaetes. Several species of demersal fish, including Urophycis sp., Ophichthus cruerifer, and Macrozoarces americanus, were present in bottom photographs taken at Stations 17 and 18.

Abundance and Diversity of Infauna. The average number of individuals per 0.04-m^2 sample ranged from 100 to 400 at some stations (eg., Stations 1, 11, and 17) to 1000 to 2000 at others (eg., Stations 5-1 and 13). At many stations, particularly the deeper ones (eg., Stations 3, 8, and 9), average densities remained relatively constant over the 12 sampling periods. The greatest fluctuations in infaunal densities among different sampling times occurred at Stations 10 and 13. At Stations 4 and 10 along the 60-m isobath, samples occasionally were dominated by large numbers of the sand dollar, Echinarachnius parma, or the archiannelid Polygordius sp. A. Analysis of replicate samples

from each cruise and bottom photographs taken at these stations revealed that these species had a very patchy distribution.

At Station 13, there was a marked decline in the number of individuals per 0.04 m^2 from a mean of about 1690 individuals in February 1982 to a mean of about 530 individuals in May 1982 (Figure 8). Density then returned to nearly 2000 individuals per 0.04 m^2 by July 1982. Density at this station them fluctuated between 1400 and 2000 individuals per 0.04 m^2 for the remainder of the monitoring program. The decline in infaunal density at Station 13 in May 1982 during the period of active drilling on Georges Bank could have been due to a winter storm or to slight differences in station location from cruise to cruise. There is a great deal of spatial heterogeneity in sediment grain size in the eastern Mud Patch. Silt + clay concentrations in sediments from Station 13 ranged from 17 to 55 percent over the course of the 12 cruises. These differences in sediment grain size, however subtle, could account for the significantly lower infaunal densities of many species at this station in May 1982.

Clear seasonal patterns of density were not apparent at most stations. However, long-term fluctuations were observed at some stations. For example, average infaunal densities at Station 5-1, the site of drilling in Block 312, were higher in years 2 and 3 (after drilling) than in year 1 (before and during drilling) (Figure 9). In Contrast, there was little variation in infaunal density over the three years of monitoring at Station 16, the site of exploratory drilling in Block 410 (Figure 10). At Station 7A, in 167 m water depth in Lydonia Canyon, infaunal densities were substantially higher in year 3 than in year 2.

At most stations, the 10 dominant species varied little from one season to another over the three years of sampling. Polychaetes were the most abundant among the dominants, followed by crustaceans. The amphipod, Ampelisca agassizi, the dominant at seven of the regional stations, also was the most abundant

species overall in the Georges Bank samples.

In order to gain further insight into the benthic community dynamics at the two drilling sites monitored, the temporal patterns of abundance of several dominant polychaete and amphipod species at Stations 5-1 and 16 were examined. At Station 5-1, most species showed the same trend as total numbers of individuals, with an increase in average abundance in years 2 and 3 in comparison to year 1.

However, there were two notable exceptions. The amphipod Erichthonius fasciatus, an epifaunal species associated with coarse sediments, completely disappeared from Station 5-1 and some nearby site-specific stations in February 1982, shortly after drilling began (Figure 11). It reappeared in May 1982 and then experienced another sharp decline in abundance in November 1983. These shifts in abundance of E. fasciatus corresponded to increases in the percent of coarse fractions in the sediments, probably storm induced, and not specifically to drilling discharges.

Another amphipod, Unciola inermis, showed large temporal fluctuations in abundance at Station 5-1 and other site-specific stations (Figure 11). In each of the three years of the study, th of u. inermis at Station 5-1 decreased progressively from July to November to a low in February, followed by a substantial increase in abundance in May. During the first year of the monitoring program when drilling was taking place in Block 312, a similar seasonal pattern of abundance was observed for this species at Site-Specific Stations 5-10 and 5-25, located 1 and 4 km, respectively, west (downcurrent) of the drilling site where significant amounts of drilling mud barite accumulated in sediments during and after drilling. At Site-Specific Stations 5-2 and 5-8, 0.5 km east and 1.0 km north of the drilling site, respectively, lowest abundances of u. inermis were observed in November 1981, just before drilling began. At Site-Specific

Station 5-28, abundance of this species increased between July 1981 and February 1982 and then decreased in May 1982. These seasonal fluctuations in the abundance of U. inermis at stations where drilling mud barite accumulated during and after drilling appear to be due to small seasonal changes in sediment grain size at the different stations and to seasonal reproductive cycles in this annual species. There was a significant inverse correlation (Spearman rank correlation coefficient, $p<0.05$) between the abundance of U. inermis and the percent fine sand at site-specific stations in February 1982. The largest percentage of gravid females occurred in seasons when total abundance of this species was low (November or February) and the highest abundance of juveniles occurred when total abundance was high (May and July).

Several species of infaunal polychaetes showed peak abundances at Station 5-1 in May and/or July 1982, during or immediately after drilling in Block 312. During the remaining two years of the monitoring program, these species did not demonstrate any consistent seasonal patterns of abundance.

In Block 410, sediment grain size and benthic infaunal community structure at Station 18, 2.0 km west of the drill site, were different from those at Station 16, within 200 m of the drill site, and at Station 17, 2.0 km east of the drill site. The dominant species at Station 18 was the amphipod, Ampelisca agassizi, whereas the dominant species at Stations 16 and 17 was an undescribed species of the polychaete, Paradoneis n. sp. A. During the first year of monitoring, the abundance of Paradoneis n. Sp. A at Station 16 declined between July 1981 (just before drilling began in Block 410) and November 1981, followed by a large increase in abundance in February 1982 and a subsequent decline in May 1982. The same seasonal pattern of abundance was observed for Ampelisca agassizi at Station 18 during the first year of monitoring. The seasonal patterns of abundance of these two species were not observed during the first year of monitoring

at the other two stations near the drilling site in Block 410, or in the subsequent two years of the monitoring program at any of the three stations. At Station 16, there was a general trend toward increasing abundance of most infaunal species during the three years of monitoring. There were no repeated seasonal trends of abundance of any species at the three stations in Block 410.

Patterns of Shannon-Weiner diversity (H′) of benthic infauna were similar for all three years of the monitoring program. The shallower Stations 1, 4, 10, and 15 had the lowest diversities, whereas stations at 100 m or deeper had the highest diversities. The lowest diversity and greatest variability in H′ were observed at Station 4, where H′ ranged from 1.11 in November 1982 to 3.07 in June 1984. At the two stations within 200 m of rig sites (Stations 5-1 and 16), diversity was lowest in February and November 1983 at Station 5-1 and in February 1982 and November 1983 at Station 16. At both drilling sites, most community parameters, including total mumber of species and diversity, generally were higher in years 2 and 3 than in year 1, and were similar between years 2 and 3 (Figures 8 and 9).

Cluster Analysis. The very large number of individual benthic infaunal samples necessitated a two-step process of analysis. In the first step, the six replicates at each station for any one sampling date were analyzed as independent samples. All of the replicates for a given station and sampling date were more similar to each other than to replicates from any other station, with two exceptions. Replicates from Stations 16 and 17, separated by 2 km in Block 410, tended to cluster together. In February 1982, but not at other sampling times, one of the Station 8 replicates clustered with replicates from Stations 16 and 17. These results indicate excellent replication of samples within a station at each sampling time and allowed the detection of subtle spatial and temporal differences in community structure.

Because of the close similarity of replicates from a particular station and sampling time, it was possible in the second stage of the cluster analysis to examine the relationship between samples formed by adding together the six replicates from a station within each sampling date. The Georges Bank stations were sufficiently invariant over the entire three year monitoring period that every sample showed more affinity with other samples from that station than with samples from any other station, regardless of sampling time and despite faunal similarities with other stations. Fauna at deeper stations showed some differences after the the first year. However, there was little evidence of seasonality at any station despite the obvious fromation of sediment ripples during the winter at nearly every station.

Stations tended to cluster together according to water depth and sediment grain size distribution (Figure 10). Stations 1, 4, and 10 along the 60-m contour grouped together. Sediments at these stations contained primarily fine and coarse sands and practically no silt/clay. Stations 2 and 5-1 in 80 m of water clustered together, while the other station at this depth, Station 11, clustered separately. Sediments at Stations 2 and 5-1 were predominantly coarse sand, while those at Station 11 were predominantly fine and very fine sand with approximately 3 percent silt/clay. Stations 3, 6, and 12 along the 100-m isobath had roughly similar sediments and clustered together. Stations 7 and 9 at the heads of Lydonia and oceanographer Canyons, respectively, clustered together, whereas Station 7A, located just inside Lydonia Canyon, clustered separately. Station 7A had fine-grained sediments and clustered with the other stations with fine-grained sediments, Stations 13, 13A, and 14A.

Cluster analysis of the site-specific stations showed that the westernmost stations, Stations 5-25 and 5-29, were quite distinct from all the other stations in the site-specific array. For some cruises, stations south of the rig site (Stations 5-11, 5-12, and 5-20) clustered with Station 5-25. These stations, and

particularly Station 5-29, have finer-grained sediments than other stations in the array. If the discharge of drilling mud and cuttings from the rig had an effect on the benthic communities, the stations nearest the rig, and particularly to the west of it, should have clustered together and partially obscured this east-west transition. This was not the case. A careful examination of faunal similarity and sediment grain size indicated that shifts in the distribution of fine sand during the winter had an important influence on these communities.

Stations 5-1, 5-18, and 5-28 in the site-specific array in Block 312 were compared (Figure 12). These three stations formed three clusters corresponding to 1981, 1982, and 1983-84, with Stations 5-1 and 5-18 behaving like replicates. Station 5-28, the easternmost station in the site-specific array, formed a discrete cluster in 1982 and 1983-84. In 1981, Station's 5-1 and 5-18 were more similar to one another than to Station 5-28. The fact that Stations 5-1 (200 m from the rig site) and 5-18 (2 km west of the rig site) always clustered together during the period when drilling was taking place in Block 312, suggests that drilling discharges had no effect on benthic community structure.

Spearman rank correlation was used to compare community similartiy to sediment composition and sediment barium concentration (the most useful tracer of drilling mud solids in sediments) at the site-specific stations. The barium concentration in the fine fraction of the sediment and the ratio of total barium concentration from July 1981 (before drilling) to July 1982 (after drilling) were used. The sediment data used in the analysis were means of percent fine sand and percent silt-clay for all sampling times. Two community measures were used: NESS similarity at 200 individuals of replicates summed from each station in the site-specific array for July 1982, compared to NESS for Station 5-28 for July 1981; and the mean of the 36 similarities obtained by measuring similarity between each of the six replicates at a particular site-specific station in

July 1982, compared with each of the six replictes at the same station in July 1981. Station 5-28 was used for comparison because it is the furthest east (upcurrent) from the drilling site of the site-specific stations. The correlation of the two community measures with the two barium parameters was not significant ($p \geq 0.15$). The correlation of community parameters with percent silt-clay also was not significant, but the correlation of community parameters with percent fine sand was significant ($p=0.03$).

DISCUSSION

The southern flank of Georges Bank is a high energy environment. Seasonal storms have a marked effect on the distribution of sediment texture out at least to the shelf/slope break. At nearly all stations sampled in this program, the sediment surface texture changed seasonally from relatively smooth in the spring and summer to rippled and sculptured in the fall and winter months. The rippling was undoubtedly due to storm-induced currents. parmenter et al. (1983) used a sediment trap to Study sediment resuspension during the winter at a location in 62 m of water on the southern flank of the Bank. Bottom current speeds during the deployment ranged from 10 to 50 cm/sec. Bottom stress, computed from the observed currents and waves, suggested that 11 storms during the winter of 1978-79 caused sufficient stress to resuspend fine sand sediments (3 phi mean grain size).

The mean general water circulation over Georges Bank is in the form of a clockwise gyre, with the direction of the mean current flow along the southern flank of the Bank toward the southwest (Butman et al., 1982). Mean current speeds range from about 10-15 cm/sec at the surface to about 5 cm/sec near the bottom and increase offshore. At depths greater than about 60 m, this mean flow is continuous with the net southwestward current flow in the Middle Atlantic Bight (Chapman et al., 1986). Thus,

materials discharged to surface waters of the Bank will tend to be carried southwestward toward the Middle Atlantic Bight or entrained in the Georges Bank gyre.

A variety of physical environmental factors, particularly semidiurnal tides and wind stress, contribute to substantial variation in the short-term current direction and speed of the flow on Georges Bank (Butman et al., 1983; Tee, 1985). Typical water particle excursions associated with low-frequency currents are 10-20 km along-shelf and 5-10 km across-shelf. Displacements associated with semidiurnal tidal currents are typically 10 km on the crest of the Bank and a few km on the flanks, with the greatest excursions in an across-shelf direction (Butman et al., 1982). Thus, the direction of drift of suspended particles from a point source (eg., a drilling platform) on the southern flank of the Bank may be in any direction, even though the predominant long-term direction of net movement will be with the mean flow toward the southwest.

The results of the investigation reported here are in agreement with this generalization. The distribution of drilling fluid solids, as evidenced by the distribution of elevated barium concentrations in sediments, was predominantly oriented in a westerly direction from the two platforms monitored. However, the re was evidence of drilling mud solids transport in other directions, even in an easterly direction opposite the mean flow. Both barium and petroleum hydrocarbons (presumably derived from drilling fluid discharges) were present at slightly elevated concentrations in bulk sediments from several stations in the immediate vicinity of the platform in Block 312 after drilling. In Block 410, slightly elevated barium concentrations were observed both west and east of the drilling site.

The results of the present investigation also indicated that there was resuspension and net westward redistribution of drilling mud barium at stations around the drill site in Block

312 in the two years after drilling was completed. The two mechanisms by which barite particles might escape from the surficial sediments of the site are by suspended or bed-load transport away from the site and by downward mixing and exchange with uncontaminated deeper sediments. Drilling mud barite has a grain size predominantly (>97 percent) below 63 um. Bottom stresses on Georges Bank are frequently greater than 1.7 dynes/cm^2 (Butman and Moody, 1983), the stress required to resuspend barite particles 63 urn in diameter. Thus, nearly all of the drilling mud barite in surficial sediments will be moved frequently by resuspension, and this is probably the major mechanism of the initial rapid removal of drilling mud barite from the sediments in the vicinity of the drill site after completion of drilling.

The slower rate of barite disappearance from surficial sediments after Cruise 8 probably is due to a combination of downward mixing of the remaining barite into deeper sediments and deposition of clean sediments in the area. Thus, this phase of decrease in barite concentration in surface sediments was due to dilution and not advection of barite from the site. Although Georges Bank as a whole is considered to be eroding, processes of sediment redistribution and local accumulation have been identified (Twichell, 1983), and probably occur on a seasonal basis in the region of the site-specific array as evidenced by seasonal and longer term changes in sediment grain size distributions.

There are two possible fates for the barite that was discharged from the drill rig and subsequently eroded from the surficial sediments near the drill site. Some of the barite could have dissolved in seawater. There is some evidence that barite deposits in surface sediments around drill sites are gradually dissolving (Trefry et al., 1985; Boothe and Presley, 1985). Seawater is udersaturated with respect to barite (Hanor and Chan, 1977; Dehairs et al., 1980), SO that despite its very low

volubility in seawater (about 50 ug/l: Burton et al., 1968), barite will dissolve slowly. Boothe and Presley (1985) concluded, based on mass balance calculations and laboratory dissolution experiments, that more than half of the barite deposited in surficial sediments around some Gulf of Mexico drilling sites dissolves. Barite that is mixed downward in the sediments may come to reside below the redox potential discontinuity. Under reducing conditions, sulfates are reduced to sulfides and barium volubility increases. Barium ion then may diffuse upward until it reaches sulfate-rich (oxic) interstitial water and precipitates. In support of this hypothesis, Trefry et al. (1985) reported concentrations of barium in interstitial water of surficial sediments near drilling sites in the Gulf of Mexico in excess of 30 ug/l, compared to a barium concentration of 10 ug/l in the overlying water column. Any drilling mud barite dissolving in the ocean would be diluted rapidly to background concentrations in the water column.

The second and probably more important fate of drilling mud barite (and by implication, all drilling mud solids) is linked to sediment transport processes. Over time, surficial sediments containing barite and other drilling fluid solids were resuspended and transported out of the area of the site-specific array. Evidence that this took place is provided by the observation of a gradual increase in the concentration of barium in the fine fraction of surficial sediments at Stations 10 and 12 west of the site-specific array and at Stations 2 and 3 to the east of the site-specific array after the completion of drilling on Georges Bank. Increases in barium concentration also were observed after drilling in surficial sediment samples collected 50 km west of transect 111 (Stations 10, 11, and 12) and in sediment traps deployed at the head of Lydonia Canyon (near Station 7) (Bothner et al., 1985). However, there was no evidence of an increase in the concentration of barium in surficial sediments at Stations 13 and 13A in the Mud Patch, an area of suspected deposition of fine sediments from Georges Bank. This

was probably due to the fact that sediments from these stations are naturally high in barium, and, therefore, a small increment in barium is difficult to detect. Bothner et al. (1983) estimated that perhaps as much as 60 to 80 percent of the barite released in drilling fluids to Georges Bank from all eight exploratory wells remains in sediments within an area extending from about 130 km west to 80 km east of Station 5-1. The remainder has either been transported completely off the Bank or has dissolved.

Although petroleum hydrocarbons, presumably derived from discharge of drilling fluids containing diesel fuel additive, were detected in sediments at only a few site-specific stations, their behavior after cessation of drilling in Block 312 was similar to that of drilling fluid barite. At most stations where they were detected, petroleum hydrocarbon concentrations returned to the range of background concentrations rapidly after completion of drilling. The main mechanisms of removal of petroleum hydrocarbons from surficial sediments are dissolution, biodegradation, and resuspension and transport from the site (National Academy of Sciences, 1985).

Earlier investigations of the concentrations of hydrocarbons in sediments of Georges Bank have revealed that total hydrocarbon concentrations range from about 0.2 to 20 ppm and total polycyclic aromatic hydrocarbon concentrations range from about 1 to 100 ppb (Boehm and Barrington, 1984; Boehm and Requejo, 1986). Hydrocarbon concentrations in sediments are directly correlated to sediment TOC concentration and inversely correlated to sediment grain size. Hydrocarbon assemblages associated with sandy sediments are derived almost equally from petrogenic and pyrogenic sources, whereas hydrocarbon assemblages associated with fine grained, clay sediments are predominantly of pyrogenic origin. Aromatic hydrocarbon concentrations in sediments collected in this program from the immediate vicinity of the rig site in Block 312 before drilling began are similar to those reported by Boehm and Barrington (1984) in sediments from

the same area in 1978. The increases in aromatic hydrocarbon concentrations during drilling were small and total aromatic hydrocarbon concentrations were still well within the range reported for relatively clean sediments from the outer continental shelf of the U.S. north Atlantic coast. It is probable that there was not sufficient accumulation of petroleum hydrocarbons from drilling fluids in the sediments to cause deleterious impacts in the benthos.

There was no accumulation of metals or petroleum hydrocarbons in the tissues of ocean quahogs Arctics islandica or four spot flounder Paralichthys oblongus during or after drilling that could be attributed to drilling mud discharges. Concentrations of barium in the soft tissues of quahogs ranged from 0.187 to 2.61 ppm. These concentrations are within the range of the limited published values for barium concentrations in marine bivalve molluscs. Different tissues of mussels, Mytilus Spp. from southern California contained 0.19 to 8.27 ppm barium (Chow and Snyder, 1980); soft tissues of oysters Crassostrea virginica from the Gulf of Mexico contained a mean of 0.65 ppm barium (Rubinstein et al., 1980); commercially harvested hard shell clams Mercenaria mercenaria from the coast of Maine contained 3.4 to 16.1 ppm barium in soft tissues (Neff et al., 1985). The few laboratory investigations performed to date indicate that drilling mud barium has a very limited bioavailability to benthic marine animals (Neff et al., 1985).

Hydrocarbons observed in the tissues of ocean quahogs and four spot flounder were predominantly of biogenic origin. Although one quahog sample analyzed by GC/MS contained traces of alkyl benzenes, it is unlikely that either the quahogs or the fish sampled had accumulated any hydrocarbons from the drilling mud discharges.

Because of the excellent replication of infaunal samples at a station from any particular cruise and the uniformity of the

benthic infaunal community at a station over time, it was possible in this investigation to detect very subtle changes in community parameters that might be related to drilling fluid and drill cuttings discharges. Nevertheless, there were no obvious trends of change in benthic community parameters at regional or site-specific stations that could be attributed to drilling discharges. Among the regional stations, there was a sharp decline in the number of individuals and species at Station 13 at the time of Cruise 4 during drilling. This decline occurred again, but to a much lesser extent, in the second year of the monitoring program. Because this decline during drilling was not accompanied by any chemical indication of input of drilling fluids solids to Station 13, it is not possible to attribute this event to drilling activities. The apparent decline in numbers of individuals and species at Station 13 in May 1982 probably was due to slight differences in station position in this area where there are sharp gradients of sediment composition.

No biological effects attributable to deposition of discharged drilling fluid solids and drill cuttings were observed in the benthos at the three Block 410 stations. At Station 16, the average number of individuals per 0.04 m^2 was lowest in July 1981 (before drilling began) and November 1981 (during drilling). For the remainder of the monitoring program, the average number of individuals showed a gradual rising trend. The number of species was lowest during and immediately after drilling (November 1981 through May 1982) and then remained above the predrilling level f othe remainder of the monitoring program. The Shannon-Weiner diversity index (H') was lowest during February 1982 (during drilling) and November 1983, and remained high for the remainder of the monitoring program. Measures of faunal similarity (ie., NESS and percent similarity) indicated a consistent high level of similarity of benthic infauna between the rig site Station 16 and the upcurrent reference station (Station 17). These two stations have the same dominant species. The downcurrent station (Station 18) has finer-grained sediments

than Stations 16 and 17 and has a slightly different benthic infauna than at Stations 16 and 17.

No biological impacts in the benthic infauna attributable to drilling discharges were detected at the site-specific stations. During drilling in Block 312, there was an increase in both the average number of individuals per 0.04 m^2 and the total number of species at the rig station (Station 5-1). The Shannon-Weiner diversity index (H') at Station 5-1 remained relatively constant during the whole monitoring program. For the period from July 1982 to June 1983 (Cruise 5 - 12), the average numbers of individuals and numbers of species remained high, with a drop in the number of species in May 1984. The fluctuations in these parameters appeared to be annual, with only a small seasonal component.

The other site-specific stations exhibited a similar pattern of infaunal community parameters. In most cases, the average number of individuals per 0.04 m^2 was lowest in November 1981 (just before drilling began) for stations within 1 km of the drill site. Species abundance also was lowest in most cases in November 1981. There was an increase in the number of individuals and number of species at nearly all site-specific stations between February and July 1982, during most of which time drilling was taking place in Block 312. Those species that showed the most marked decline in abundance in November 1981 or February 1982, such as the amphipod Leptocheirus fasciatus and Unciola inermis, showed substantial recovery by May or July 1982. These seasonal patterns of abundance of some species probably are related to seasonal changes in sediment texture due to winter storms and seasonal reproductive/recruitment patterns. Cluster analysis of the infauna data from the site-specific stations indicated some year to year changes in similarity, but none of these were related to changes in sediment barium concentration. Site-specific stations where barium accumulated during or after drilling never clustered separately from stations where barium

did not accumulate. Thus, we can conclude that discharge of drilling fluids and drill cuttings from the rig in Block 312 and the accumulation of drilling fluid solids on the bottom near the rig site did not have a measurable effect on the benthic infauna in the vicinity of the drilling site.

The field investigation most comparable to the Georges Bank Benthic Monitoring Program was that performed by EG&G Environmental Consultants for the Offshore Operators Committee around an exploratory rig site in New Jersey 18-3 Block 684 on the mid-Atlantic outer continental shelf approximately 156 km east of Atlantic City, New Jersey (Mariani et al., 1980; Menzie et al., 1980, Gilmore et al.,1981, 1985; Maurer et al., 1981, 1982; EG&G Environmental Consultants, 1982). The rig was located in 120 m of water, comparable to depths of 79 and 142 m for the two exploratory rigs in Blocks 312 and 410, respectively, monitored in the Georges Bank Program. Sediments at the mid-Atlantic site contained higher concentrations of silt and clay than sediments at the Georges Bank rig monitoring sites. The velocities of bottom water currents at the mid-Atlantic site were below 10 cm/sec 62 percent of the time and below 25 cm/sec 95 percent of the time. On the southern flank of Georges Bank, the mean velocity of residual current flow to the southwest is about 3.5 cm/sec near the bottom. Superimposed on this are semidiurnal tidal currents with speeds of 35 to 75 cm/sec (Aaron et al., 1980). In addition, severe northeast storms, particularly during the winter, cause substantial bottom scour, even at the 140-m stations (Butman, 1982). Thus, the lease Sale 42 area of Georges Bank is in a higher energy environment than the Block 684 site on the mid-Atlantic outer continental shelf.

In the mid-Atlantic study, a zone approximately 150 m in diameter of visible drilling discharge accumulations (primarily clay-sized drill cuttings) was observed by bottom photographs and side scan sonar in the immediate vicinity of the well site, while elevated levels of clays were detected up to 800 m southwest

(downcurrent) of the drill site immediately after cessation of drilling. An area of heavy drill cuttings and debris accumulation about 40-50 m in diameter was observed immediately south of the well site. The height of the cuttings pile was estimated to be less than 1 m. During the second post-drilling survey one year after completion of drilling, elevated levels of clay were not detected southwest of the drill site. In surveys immediately after and 1 year after drilling, concentrations of barium in the upper 3 cm of sediments were high (up to 3,477 ppm in the first post-drilling survey and 2,144 ppm in the second post-drilling survey compared to 148-246 ppm in predrilling sediments) near the drilling site and decreased with distance from the site. Elevated concentrations of barium were detected in bulk sediments up to 1.6 km from the drill site. There were no elevations in the concentrations of chromium or other metals in sediments near the rig site after drilling.

In the Georges Bank study, small amounts of cuttings (up to 1-2 percent) were detected in surficial sediments within about 200 m of the rigs in Blocks 312 and 410. No cuttings pile was visible in any bottom photograph. Elevated barium concentrations were detected in bulk sediments from several stations near both drill sites after drilling, but increments were never more than about 8-fold.

The abundance of infauna in the vicinity of the mid-Atlantic rig site was higher than that at the nearby ELM Benchmark Station (Boesch, 1979) before drilling (8,011 individuals/m^2 versus 3,064 individuals/m^2). At the rig site, infaunal abundance dropped to 1,729 individuals/m^2 immediately after drilling, and them rose to 2,638 individuals/m^2 one year later. These changes in abundance were the same for the four major taxonomic groups (polychaetes, echinoderms, crustaceans, and molluscs). With the exception of a few stations less than 100 m southwest (downcurrent) of the drill site that had markedly reduced benthic faunas during the first post-drilling survey,

there was no relationship between direction, distance from the rig site (out to 3.2 km), or sediment barium concentration, and the extent of decrease in the abundance of any major taxonomic group or major species.

Species richness at the rig site dropped from 70 ± 7/0.2 m^2 in the predrilling survey to 38 ± 10/0.2 m^2 immediately after drilling and then rose again to 53 ± 8/0.2 m^2 one year later. Shannon-Weiner diversity (H') and evenness (J') showed only very small changes between the predrilling and the two postdrilling surveys. Diversity decreased slightly, which probably was related in part to increased evenness in the postdrilling surveys. These changes in aereal richness, species diversity, and evenness were similar at stations near the well site and at the three stations considered to be beyond the influence of drilling discharges.

The authors concluded that there were effects of exploratory drilling on the benthic environment of the mid-Atlantic outer continental shelf and that these physical and biological effects persisted for at least a year after cessation of drilling activities. To the extent that the decreased abundance and species richness of benthic infauna around the rig site immediately after drilling were due to drilling discharges, there was evidence of some recovery during the year after completion of drilling.

The apparent lack of an impact of exploratory drilling discharges on the benthic infaunal community structure of Georges Bank compared to that observed at the mid-Atlantic outer continental shelf rig site probably is due in large part to the difference in the amounts of drilling mud solids and cuttings accumulating on the bottom at the two sites. In the lower-energy environment of the mid-Atlantic outer continental shelf, more drilling muds and cuttings accumulated on the bottom and impacts on the benthos were greater than on Georges Bank.

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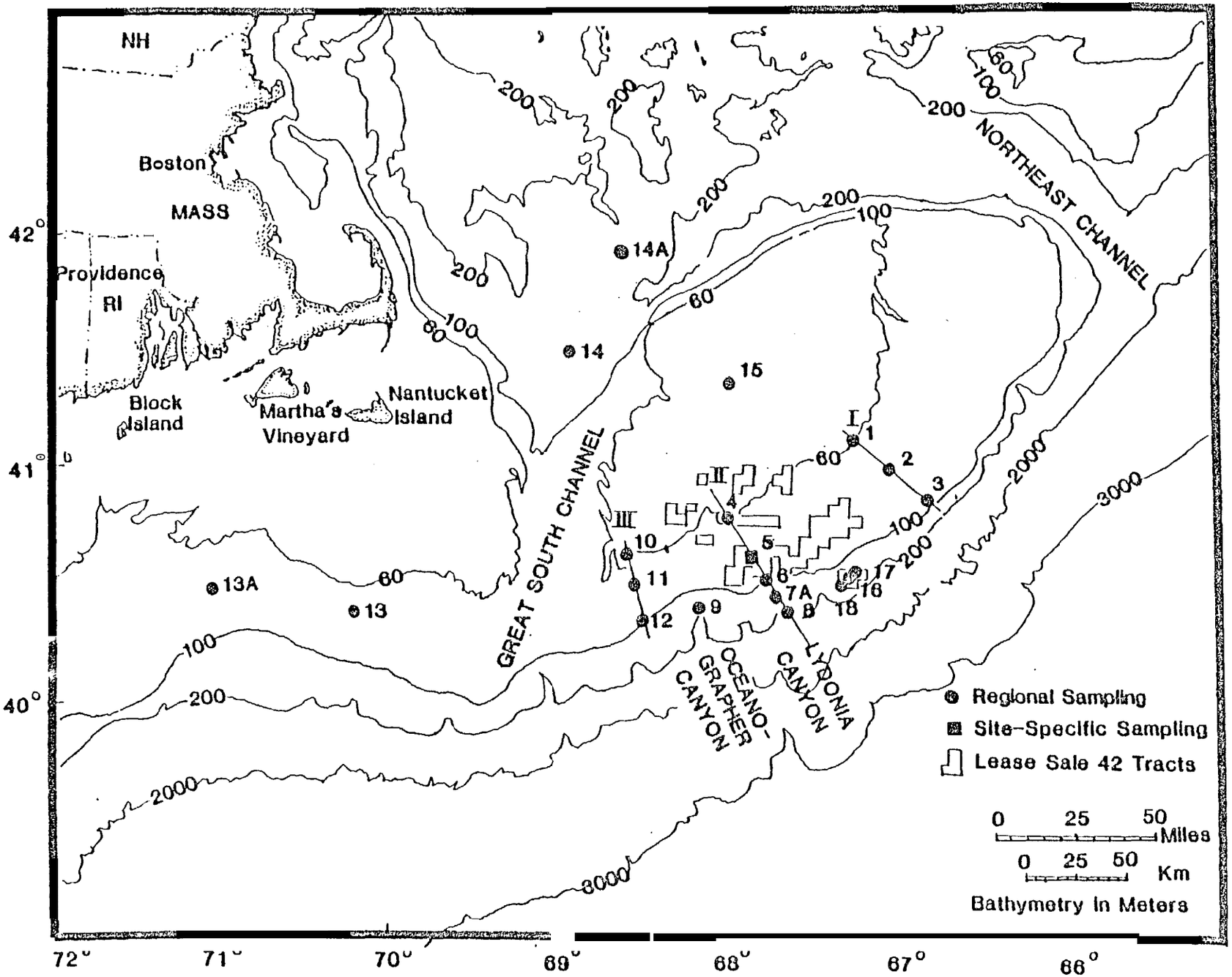

FIGURE 2. LONG-TERM REGIONAL STATIONS

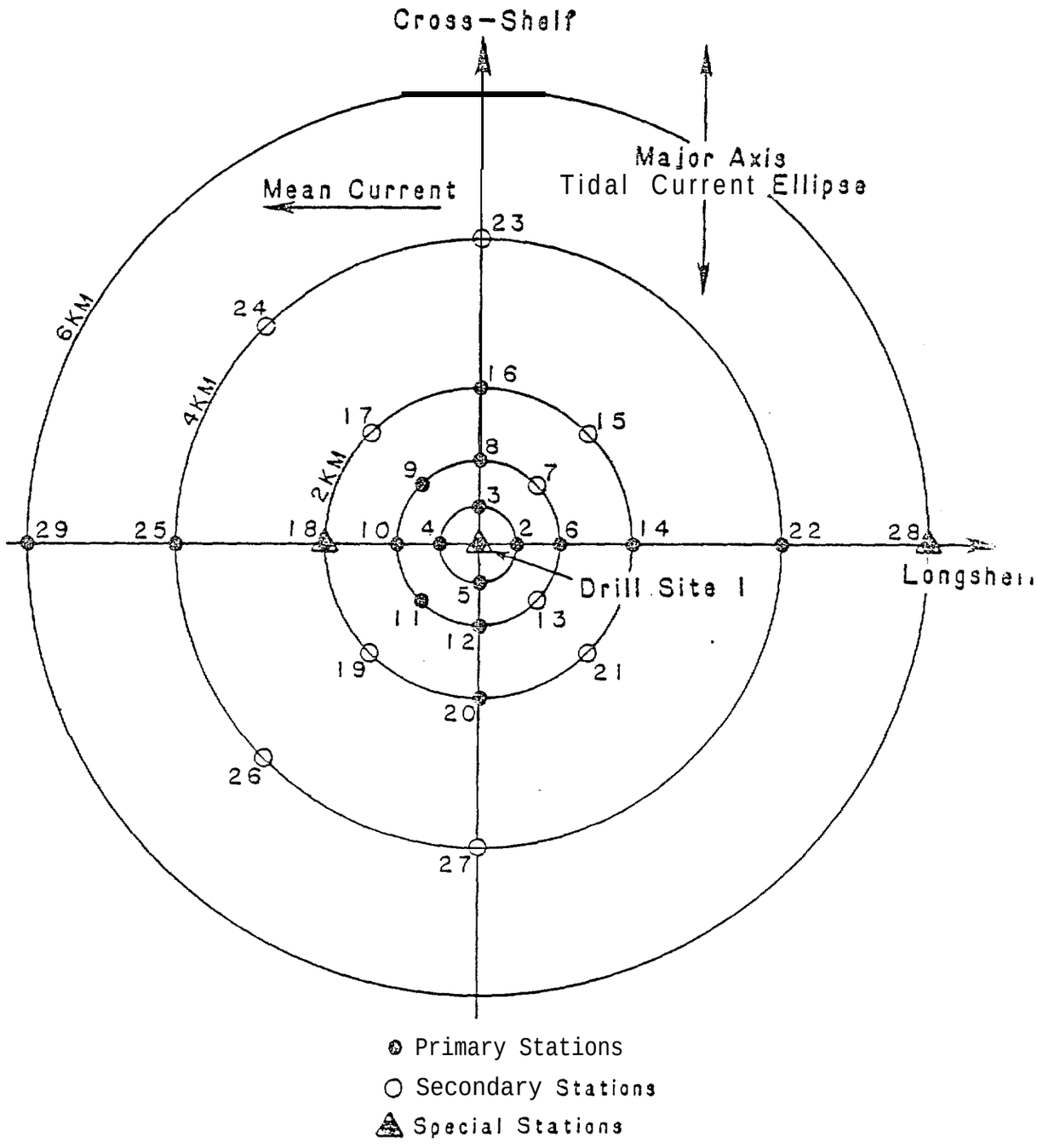

Figure 2. Site-specific stations central around Regional Station 5.

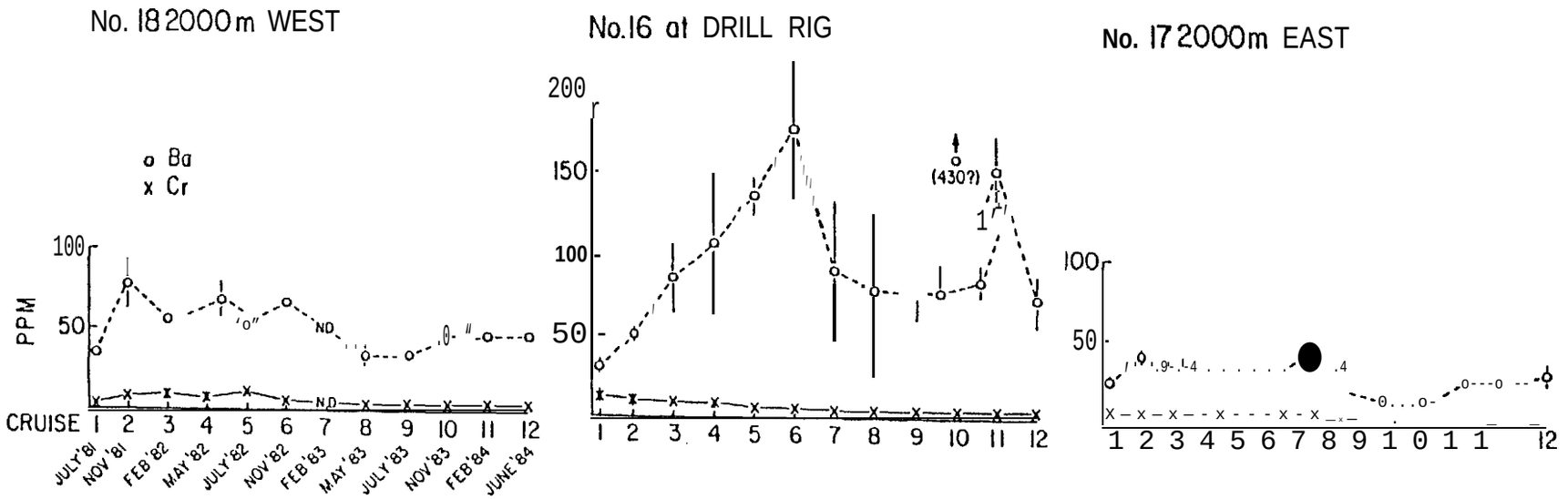

FIGURE 5. Concentrations of barium (circle) and chromium (x) in bulk sediment on different sampling occasions near the drill site at Block 410. Drilling began after the first cruise and ended prior to the fourth cruise. Error bars are one standard deviation among three individual replicates. Anomalous value of 430 ppm in one of the three replicates at station 16 was omitted from calculation of the mean. ND=no data.

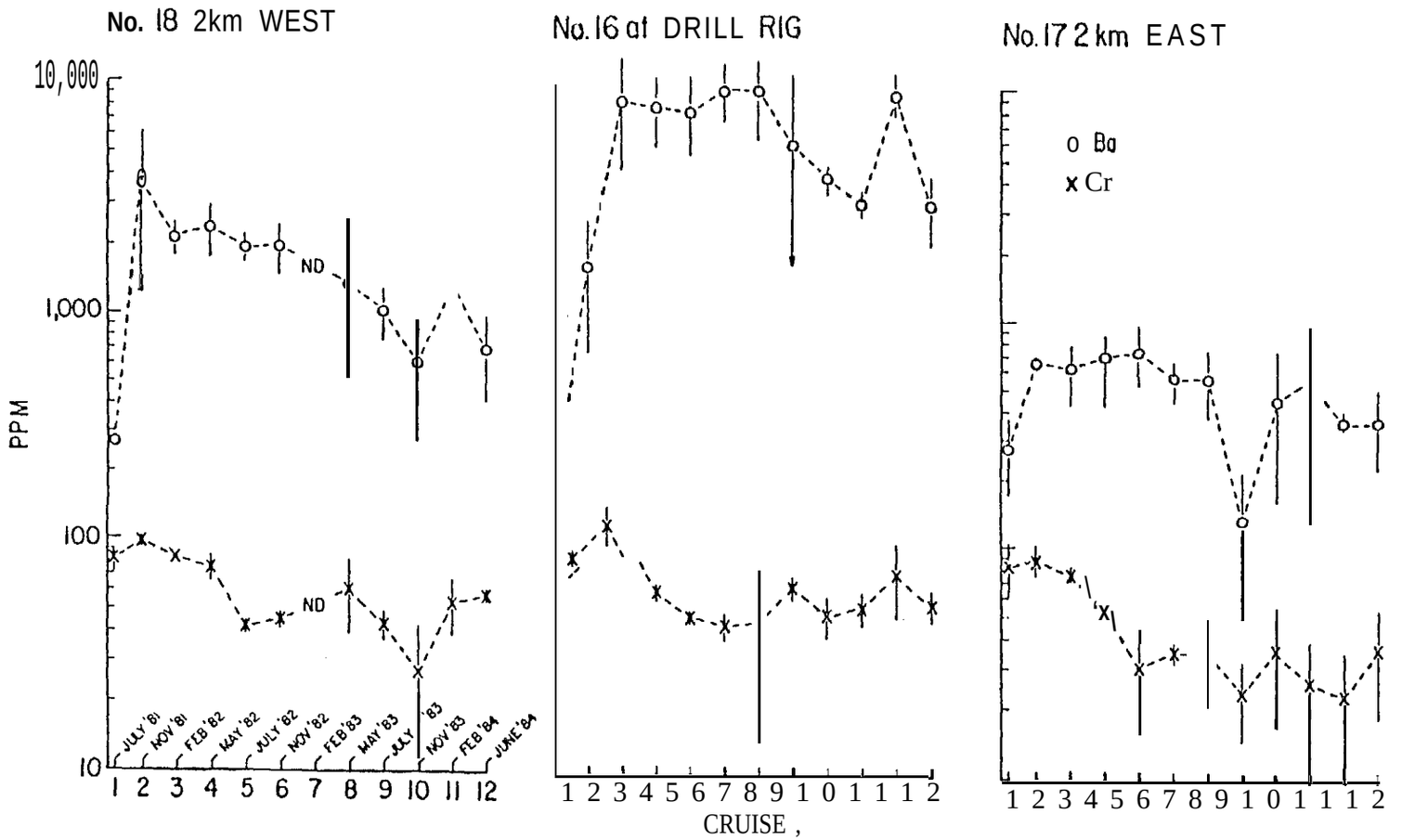

FIGURE 7. Concentrations of barium (circle) and chromium (x) in the fine fraction (less than 60 μm) on different sampling occasions near the drill site at block 410. Drilling began after the first cruise and ended prior to the fourth cruise. Error bars are one standard deviation among three individual replicates. ND= no data.

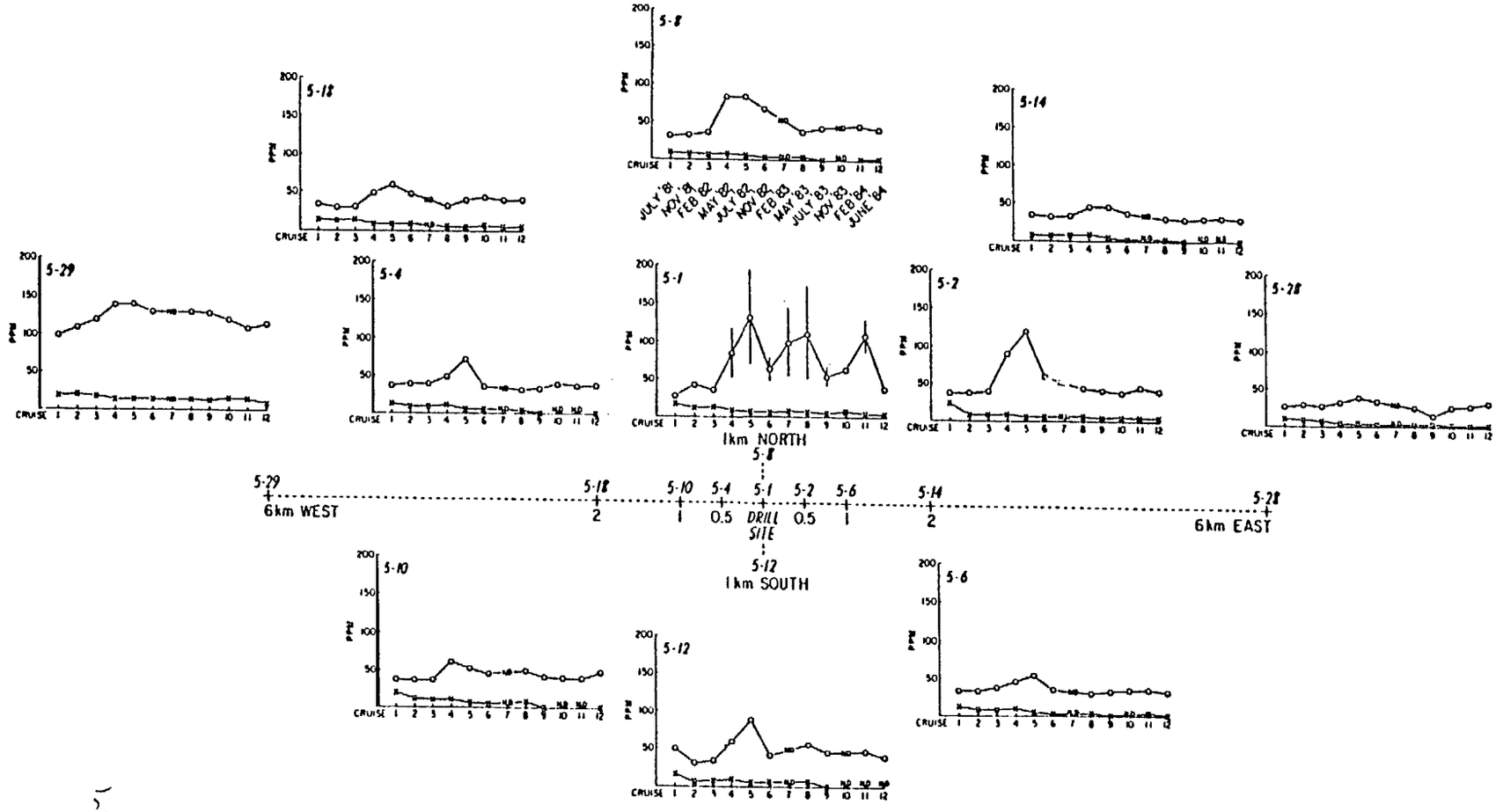

FIGURE 6. Concentrations of barium (circle) and chromium (x) in bulk sediment on different sampling occasions near the drill site at block 312. Stations are located on east-west and north-south transects through the drill site (see figure 1B . Drilling began after the second cruise and ended just before the fifth cruise. Error bars are one standard deviation among three individual replicates. ND=no data.

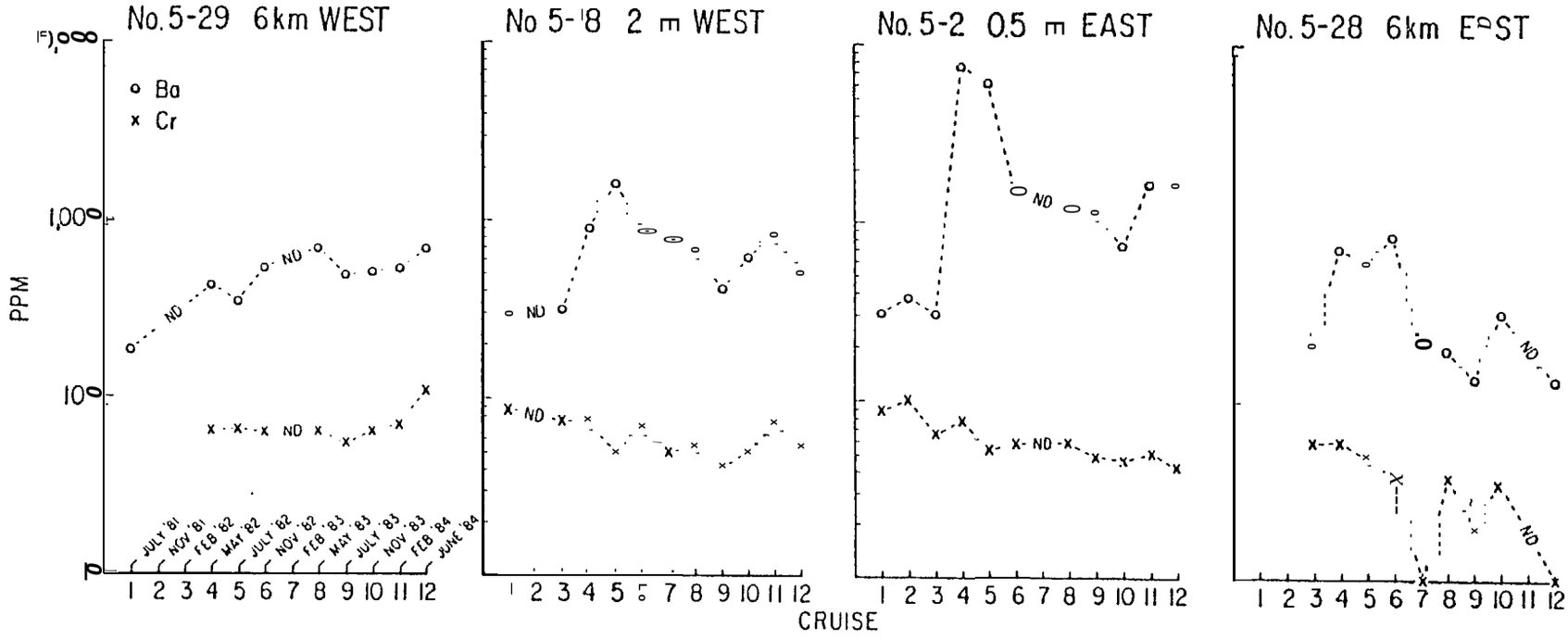

FIGURE 6. Concentrations of barium (circle) and chromium (x) in the fine fraction (less than 60 μm) on different sampling occasions near the drill site at block 312. Drilling began after the second cruise and ended just prior to the fifth cruise. ND= no data.

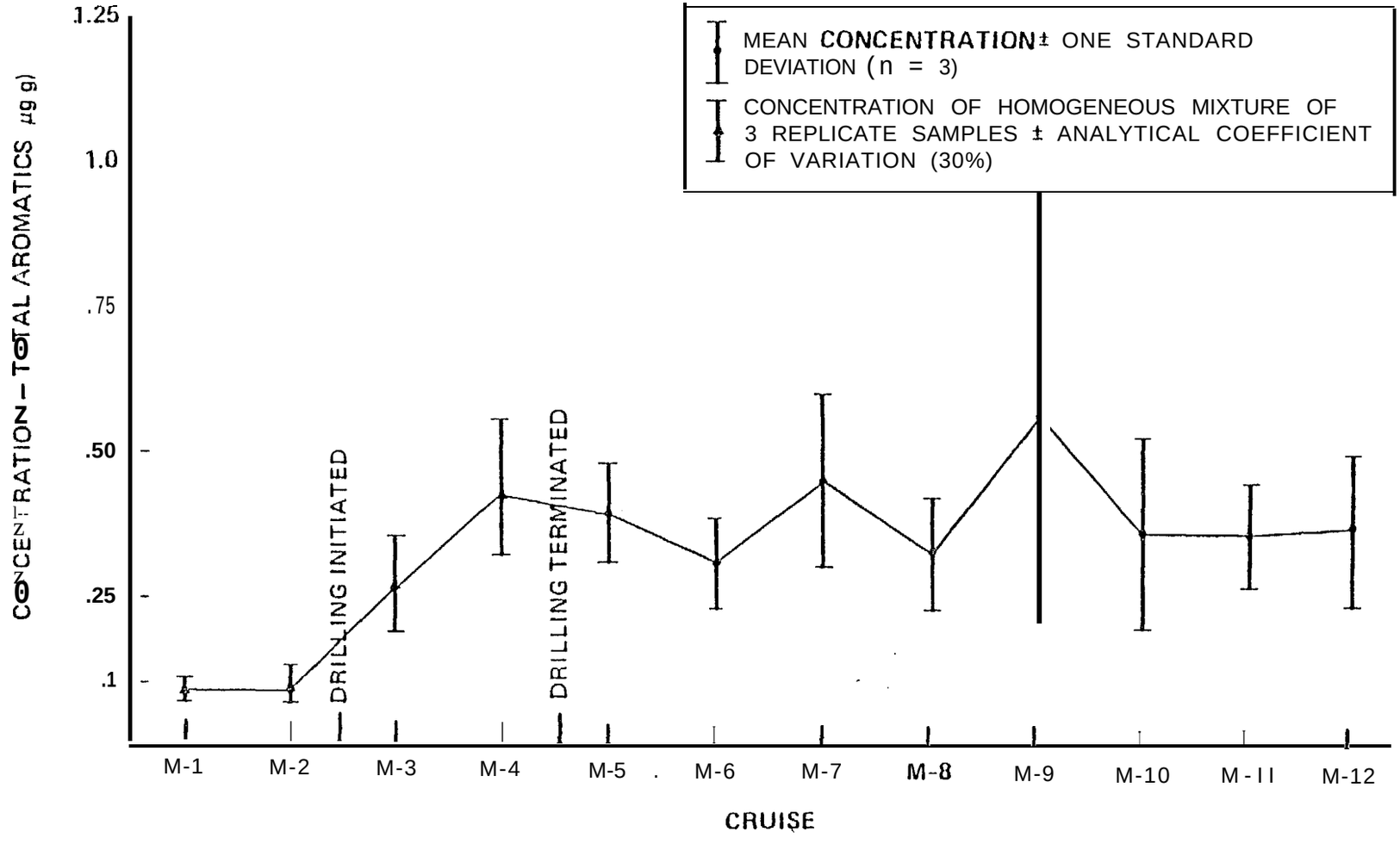

FIGURE 7. CONCENTRATIONS OF TOTAL AROMATIC HYDROCARBONS IS SEDIMENTS FROM SITE-SPECIFIC STATION 5-1 DURING CRUISES M-1 THROUGH M-12. VALUES ARE MEANS OF THREE REPLICATE SAMPLES ± ONE STANDARD DEVIATION, EXCEPT WHERE NOTED.

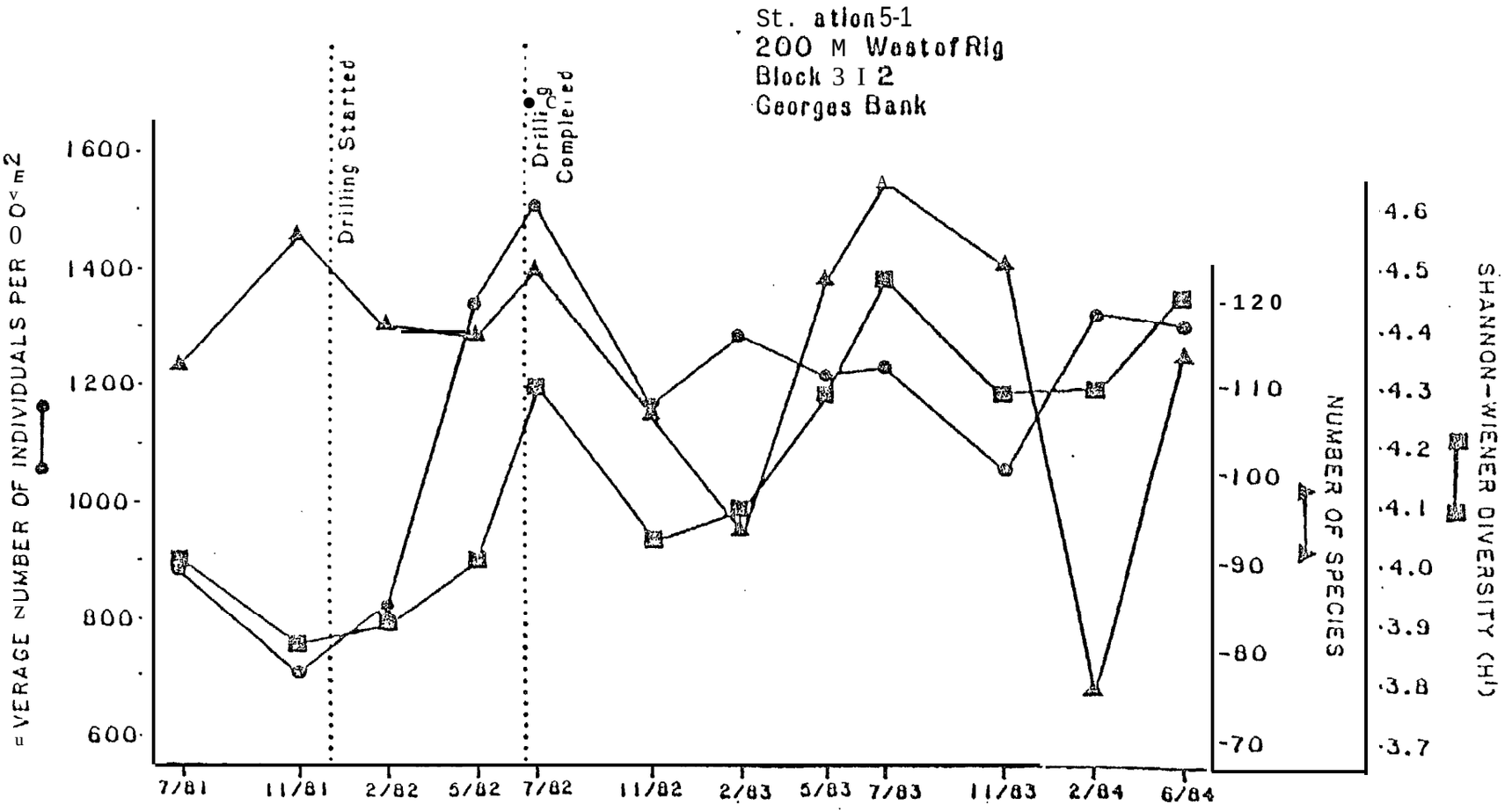

Figure 8. Average number of individuals per 0.04 m^2, total number of species in six replicate grab samples, and Shannon-Wiener diversity index (H') at Site-Specific Station 1 an 12 sampling occasions.

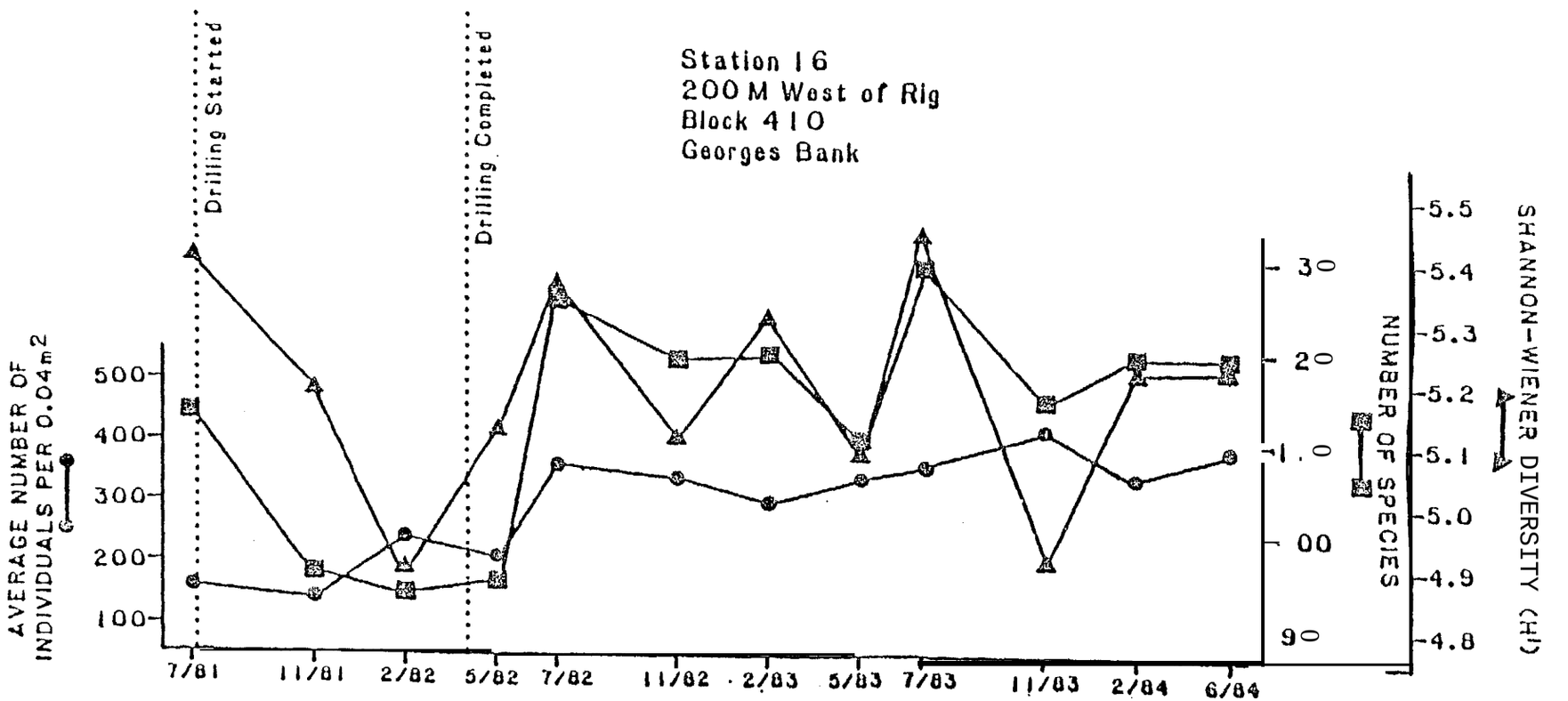

Figure 8. Average number of individuals per 0.04 m2, total number of species in six replicate grab samples, and Shannon-Wiener diversity index (H') at Regional Station 16 on 12 sampling occasions.

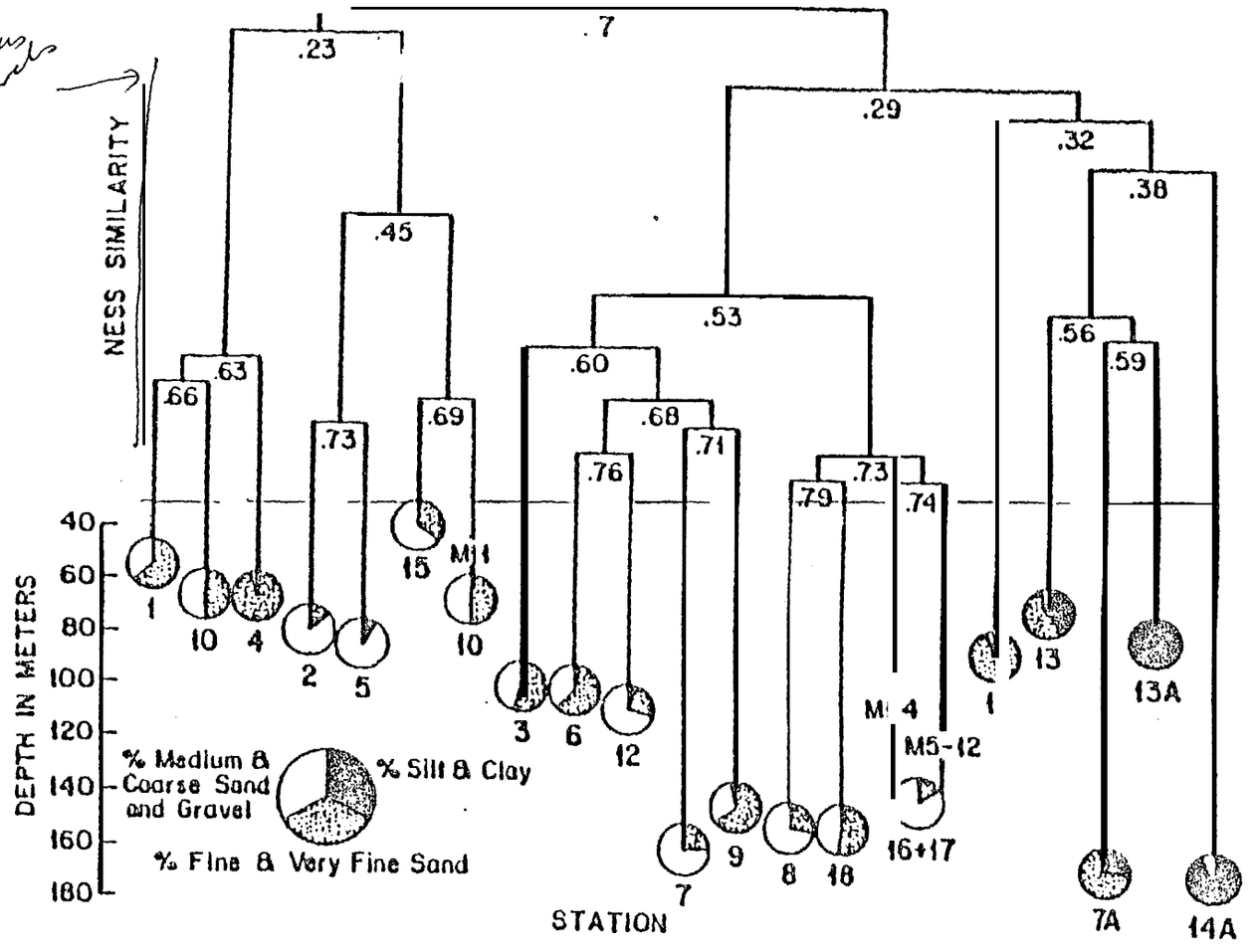

Figure 5. Summary of agglomerative cluster analysis using the sum of six replicates within each sampling date with NESS at 50 individuals and group average sorting. Results are related to station depth and sediment type. Except Station 10, February 1983 (M11), all of the samples at a given station cluster together regardless of season or year. Most stations had 11 to 12 sampling periods. Stations 7 and 15 were dropped in the last two years and had four and five sampling periods respectively. Stations 7A, 13A, and 14A were added in the second year and had eight sampling periods.

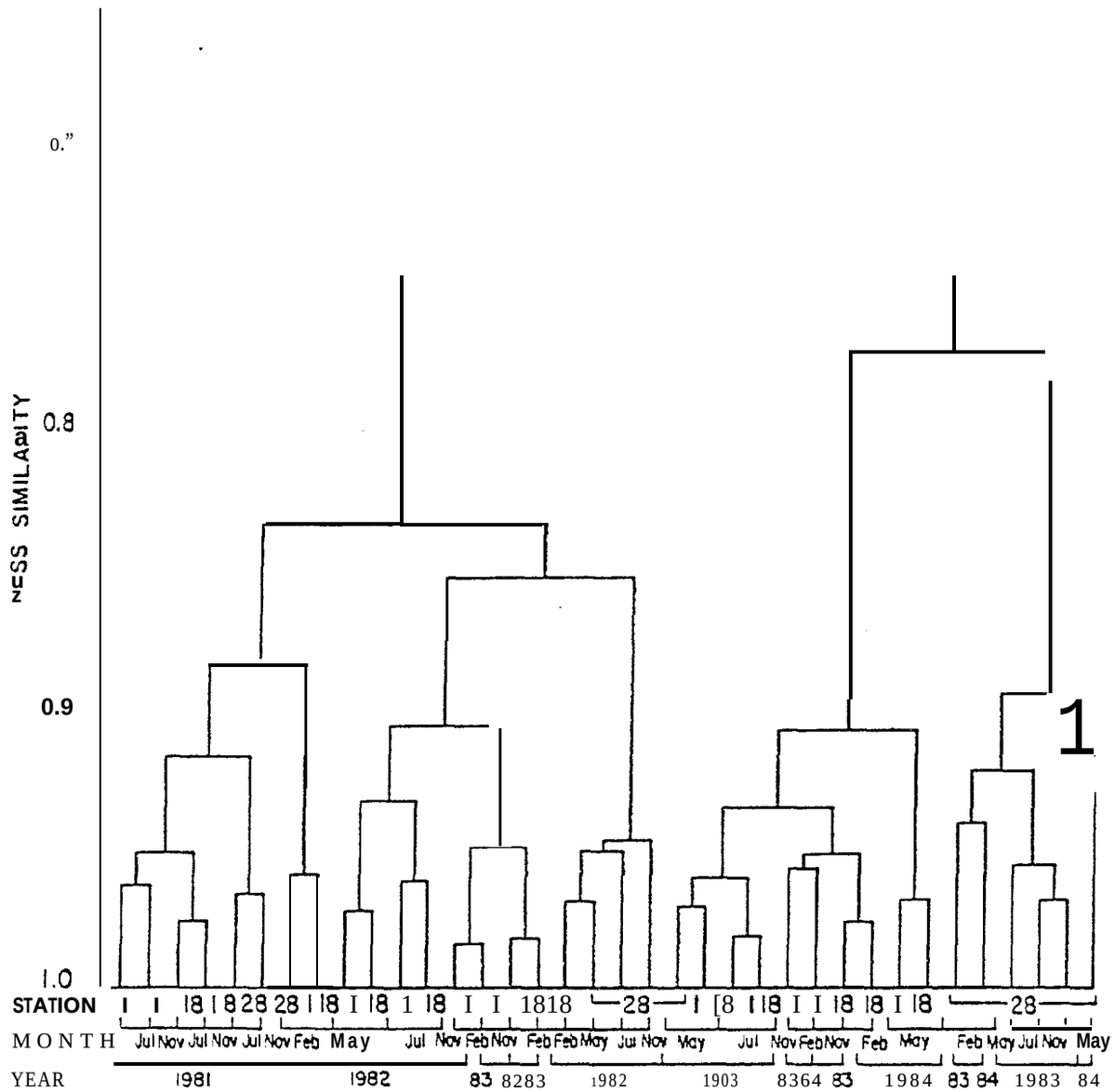

Figure 55. The sum of six replicates of samples taken at Stations 5-1, 5-13, and 5-28 for four seasons for three years. The agglomerative cluster analysis was based on NESS similarities at 200 individuals and flexible sorting (β = -0.25).

TABLE 3. SCHEDULE OF SAMPLING CRUISES FOR THE GEORGES BANK BENTHIC INFAUNA MONITORING PROGRAM.

Cruise	Date	Ship
M1	Jul 6-23, 1981	R/V Eastward
M2	Nov 9-21, 1981	R/V Oceanus
M3	Feb 10-21, 27, 1982	R/V Endeavor and R/V Asterias
M4	May 10-13, 1982	R/V Caoe Henlopen
M5	Jul 21-23, 19S2	R/V Oceanus
M6	Nov 19-23, 1982	R/V Oceanus
M7	Feb 5-11, 19S3	R/V Endeavor
M8	May 13-21, 1983	R/V Gyre
M9	011113-20, 1983	R/V Gyre
M10	Nov 13-19, 1983	R/V Oceanus
M11	Feb 1-7, 1984	R/V Oceanus
M12	Jun 2-9, 1984	R/V Gyre

TABLE 12. GC/MS Analysis of Sediment Extract : Station 5-1, Cruise [illegible] (83-910, 11 & 12); Aromatic (F2) Fraction

Retention Time	Kovat Index	Compound Identification	Concentration (rig/g dry wt)	PNA
6.98	904	C8 alkene	1.27	
8.98	955	Branched Ketone or Aldehyde	0.27	
13.39	1061	Cycloalkene	0.58	
23.10	1288	2-methylnaphthalene	1.69	*
23.78	1305	I-methyl naphthalene	1.18	*
25.57	1375	Biphenyl	0.46	*
27.50	1399	2,6-dimethylnaphthalene	1.35	*
28.08	1414	Dimethylnaphthalene	1.20	*
28.19	1417	Dimethylnaphthalene	0.58	*
30.53	1482	Propylnaphthalene or Methylbiphenyl	0.23	*
31.28	1510	Isopropylnaphthalene	1.24	*
31.65	1526	Dibenzofuran	0.34	*
32.82	1542	Trimethyl naphthalene	0.41	*
33.41	1559	2,3,5-trimethylnaphthalene	0.24	*
34.05	1577	Fluorene	0.85	*
34.47	1588	1H-fluorene or 9H-fluorene	0.24	*
34.70	1595	Trimethyl naphthalene	0*19	*
35.88	1629	Methyldibenzofuran	0.26	*
36.46	1646	Methyl dibenzofuran	0.26	*
37.15	1667	Butylnaphthalene	0.43	*
37.48	1676	C_5-naphthalene	0.67	*
37.98	1691	Alkane	0.33	
38.27	1700	Methyl 9H-fluorene	0.89	*
39.24	1730	5C-naphthalene	0.61	*
39.76	1746	Dibenzothiophene	0.67	*
40.65	1774	Phenanthrene	3.46	*
41.31	1794	C_{12} branched alcohol	0.96	
43.23	1857	Methyldibenzothiophene	0.34	*
44.65	1903	Methyl phenanthrene	0.18	*
44.98	1914	Methylphenanthrene	0.87	*
46.57	1968	1,2-benzenedicarboxylic acid, ester	0.69	*
48.33	2030	Dimethylphenanthrene	0.89	*
49.03	2055	Oimethyl phenanthrene	1.62	*
49.35	2066	Dimethylphenanthrene	0.41	*
50.48	2107	Pyrene	1.46	*
51.19	2133	3-ring PNA	0.68	*
53.81	2232	C_4-phenanthrene	0.37	*
55.27	2289	Methylpyrene	0.33	*
56.29	2330	Cyclo or branched alkane	7.40	
56.58	2342	Cyclo or branched alkane	1.63	
56.92	2356	C_{19} or C_{20}-alcohol	0.94	
60.25	2494	4-ring PNA	0.91	*
61.53	2550	FAME	0.54	
68.68	2882	Perylene	0.89	*
69,02	2899	nC-29	1.12	

Table 3. CONCENTRATIONS OF HEAVY METALS IN THE WHOLE SOFT TISSUES OF THE OCEAN QUAHOG Arctics islandica COLLECTED AT SITE-SPECIFIC STATIONS ON DIFFERENT CRUISES OF THE GEORGES BANK MONITORING PROGRAM. CONCENTRATIONS ARE IN UG/G DRY WT. + ONE STANDARD DEVIATION.

CRUISE	NUMBER	Ba	Cd	Cr	Cu	Hg	Ni	Pb	v	Zn
1	2	0.400 ±0.044	3.96 ±1.89	2.10 ±0.29	5.54 ±2.17	0.033 +0.031	17.8 ±2.19	4.50 i-3.73	0.354 ±0.199	108 ±17.7
3	5	1.08 ±0.53	4.60 ±1.72	1.52 +0.28	5.15 ±1.73	0.058 +0.016	29.1 +5.17	2.31 ±1.20	0.975 ±0.931	150 ±56.5
4	2	1.21 +0.77	4.64 +2.15	1.94 +0.21	6.00 +1.76	0.058 ±0.030	31.6 ±16.5	5.25 ±4.72	0.507 ±0.230	192 +40.3
5	7	0.977 ±0.840	4.38 +3.37	1,61 +0.97	10.8 +4.95	0.047 ±0.012	1609 +10.6	0.298 +0.160	0.293 +0.120	132 ±49 .7
6	7	1.40 +0.72	3.2a ±0.88	2.10 +0.72	7.09 ±2.30	0.042 +0.019	22.6 +6.98	0.258 +0.251	0.265 ±0.120	105 ±33.0
a	5	1.24 ±0.33	4.44 ±1.27	1.66 +0.82	4.32 +1.32	0.010 +0.005	14.9 ±7.84	0.871 ±0.303	0.393 ±0.520	119 +54.3
9	4	0.389 ±0.260	4.66 +0.690	4.02 +1.60	11.64 ±3.01	‘0.050 ‘40.012	25.7 ±5.97	3.00 ±2.06	3.02 ±2.08	172 ±16.5
11	1	0.610	6.97	4.45	9.10	0.067	23.7	7.86	2.60	128
12	1	0.659	3.20	1.80	13.6	0.031	22.4	4.70	0.650	159

TABLE 4. CONCENTRATIONS OF HEAVY METALS IN THE SOFT TISSUES OF FOURSPOT FLOUNDER Paralichthys oblongus FROM SITE-SPECIOFIC STATIONS AND REGIONAL STATION 13 FOLLOWING DRILLING. CONCENTRATIONS ARE IN UC/G DRY

CRUISE	STATION	TISSUE	NUMBER	Ba	Cd	Cr	Cu	Hg	Ni	Pb	V	Zn
4	5-1	Muscle	1	<0.016	0.010	0.014	0.781	0.520	0.047	0.072	0.265	14.5
4	5-1	Liver	1	9.09	2.19	0.165	24.0	0.370	0.122	0.856	9.12	269
4	5-28	Muscle	4	0.022 +0.001	0.022 +0.019	0.028 ±0.001	0.874 ±0.160	0.443 ±0.265	0.035 +0.017	**0.158 +0.067**	0.088 +0.011	17.7 ±4.30
4	5-28	Liver	1	4.75	1.42	0.066	15.6	0.143	0.057	**0.241**	4.45	283
4	13	Muscle	1	<0.025	0.010	0.023	0.702	0.332	0.052	0.121	0.047	15.6
5	5-14	Muscle	1	<0.077	0,038	<0.020	0.623	0.221	0.154	<0.051	0.294	20.3
5	13	Muscle	1	0.096	0.021	<0.023	0.422	0.265	0.138	<0.054	0.034	14.0
6	13	Muscle	1	<0.036	0.038	<0.014	0.602	0.353	0.095	0.036	0.061	15.2
8	13	Muscle	1	<0.016	<0.003	0.189	0.593	0.129	<0.062	0.821	0.076	14.0